Adoption Versus Adaptation, with Emphasis on Climate Change

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Annu. Rev. Resour. Econ. 2012. 4:27–206

The *Annual Review of Resource Economics* is online at resource.annualreviews.org

This article's doi:
10.1146/annurev-resource-083110-115954

JEL: D83, Q27, Q54, Q55, Q56

1941-1340/12/1010-0027$20.00

Keywords

environmental economics, resource economics, imitation, learning, diffusion, mitigation, information, risk, trade

Abstract

This article presents lessons from the rich adoption literature for the nascent research on adaptation. Individuals' adoption choices are affected by profit and risk considerations and by credit and biophysical constraints. New technologies spread gradually, reflecting heterogeneity among potential adopters, processes of learning and technological improvement, and policies and institutions. Adaptation is the response of economic agents and societies to major shocks. We distinguish between reactive and proactive adaptation. The latter is important in the context of climate change and consists of mitigation, reassessment, and innovation that aim to affect the timing and location of shocks. Adaptation strategies also include adoption of innovation and technology transfer across locations, insurance and international trade, and migration and invasions. Recent research emphasizes multidisciplinary collaborations; historical analysis; and the roles of returns to scale of key technologies, social networks, behavioral economics, path dependency, and ex ante adjustment in explaining patterns of adoption and adaptation.

1. INTRODUCTION

This article presents research on two different yet related processes of change: adaptation and adoption in natural resource economics. In attempting to understand the relationship between the two processes, we gather insights from the rich adoption literature and discuss their implications for the nascent research on adaptation. Adaptation is defined as the response of economic agents and societies to major environment changes (e.g., global warming) and/or political and economic shocks (e.g., famine or war). Recently, there has been heightened attention to adaptation to environmental changes due to concerns about climate change, a topic that we emphasize here. Adoption, defined as a change in practice or technology used by economic agents or a community, has a long intellectual history. Research on adoption was inspired by the desire to understand the adoption of modern agricultural practices and the Green Revolution. Such research has been a mainstay in resource, environmental, and development economics and has coincided with a growing interest in the adoption of conservation technologies (Lichtenberg et al. 2010).

Both adoption and adaptation require changes in methodological emphasis compared with traditional neoclassical microeconomics. Concepts derived by pioneers like Marshal and Samuelson use differential calculus to derive marginal responses to small changes, assuming well-behaved continuous relationships. Adaptation consists of responses to non-continuous changes, and similarly a significant part of adoption research is based on understanding discrete choices. Thus, the emphasis on discrete variables in adoption research has led to the development of new analytical approaches that will provide a foundation for adaptation studies.

This article first presents an overview of the main research and recent findings in the literature on adoption and innovation. We then discuss the recent works on adaptation strategies in general, emphasizing adoption, migration, and institutional change such as trade and insurance. We conclude with lessons from the adoption literature for the new literature on adaptation and make recommendations for future research.

2. ADOPTION AND INNOVATION

A large body of literature on the economics of adoption (e.g., Feder et al. 1985, Jaffe et al. 2002, Foster & Rosenzweig 2010b) distinguishes between adoption by individual agents and diffusion (e.g., aggregate adoption) and adoption of technical versus institutional innovations. Adoption is generally measured as a discrete choice and is sometimes associated with a continuous indicator: the extent of adoption. Diffusion is measured as the share of agents that adopt a technology or as shares of fixed resources (e.g., land) that utilize a new adopted technology.

2.1. Main Strains of Literature

The adoption and diffusion literature spans several disciplines, including economics, sociology, and marketing, and involves a variety of models and strains. We discuss the various models below.

2.1.1. Diffusion as a process of imitation. Empirical studies show that diffusion behaves as an S-shaped function of time. Rogers (1962) emphasizes the role of communication within social networks in accelerating diffusion and introduces a simple framework to quantify diffusion as an imitation process. Griliches (1960) shows that the speed of diffusion is faster when a new technology is more profitable. Expanded imitation models (Bass 1969) have been used extensively in marketing, and recent surveys (Mahajan et al. 1995, 2000; Peres et al. 2010) show that these models were expanded to include communication between consumers (Galeotti & Goyal 2010) and integration of marketing tools (Van den Bulte & Lilien 2001). However, the imitation model lacks a clear microeconomic foundation, namely explicit modeling of behavior by firms and individuals. The threshold model was designed to overcome the shortcomings of the imitation model.

2.1.2. The threshold model of adoption. Introduced by David (1975) and expanded by Stoneman (1983) and Feder et al. (1985), the threshold model of adoption assumes that individuals make adoption decisions using economic decision-making rules, heterogeneity of potential adopters, and dynamic processes—all factors that affect change over time. The micro-level economic decision-making criteria emphasized in the literature are static profit maximization and expected-utility maximization. Some recent studies assume dynamic optimization, whereby the timing of adoption is determined by the trade-off between the benefit from use in the present and the likelihood of a reduced price in the future (McWilliams & Zilberman 1996). Sometimes the dynamic processes that affect returns or costs are stochastic; such processes include additive and multiplicative random walk. In these cases, decision makers are taking a real-options approach, and thus timing of adoption is selected so that the marginal benefit overcomes the marginal cost plus the hurdle rates that increase with uncertainty (Seo et al. 2008).

Different sources of heterogeneity affect the timing and magnitude of adoption. One is location; higher rates of adoptions frequently occur closer to the urban center (Rogers 1962). The Internet reduces the salience of distance on adoption (Forman et al. 2005). Another source of heterogeneity is size. Foster & Rosenzweig (2010a) argue that size is a large barrier for adoption of technologies in developing countries and is a major contributor to low productivity. Thus, an increase in farm size may be a major contributor to increased productivity overall. The quality of fixed assets, including human capital, is yet another source of heterogeneity. For example, individuals with higher levels of education are more likely to adopt advanced computer software (Hellegers et al. 2011). The putty-clay approach introduced vintage as a source of heterogeneity that can trigger adoption; e.g., older machinery is more likely to be replaced within a firm (Jovanovic & Yatsenko 2010). However, a study by Comin & Hobijn (2003), which compares diffusion of technologies within countries, consistently shows a trickle-down process whereby technologies are adopted earlier in developed countries and later in developing countries. Thus, openness to trade, which enabled shipping of older vintages to developing countries, contributed to faster adoption overall.

Other dynamic processes that affect adoption include learning by doing (by the user), learning by using (by the manufacturer), network externalities (Katz & Shapiro 1986), and learning about the technology (by users and manufacturers). Furthermore, increased learning about the technology is positively correlated with experience of the user and others (Foster & Rosenzweig 1995).

2.1.3. Models of adoption as a multistage process. Rogers's (1962) seminal book divides the adoption decision into five stages: awareness, interest, evaluation, trial, and adoption.[1] This categorization models adoption as time- and effort-consuming activities and emphasizes the importance of understanding the learning and judgment associated with adoption. This literature has been developed mostly in sociology (Rogers 2003) and in marketing. Kalish (1985) distinguishes between only two stages: awareness (the state of being informed about product attributes) and adoption. He uses the imitation epidemic-type framework to model awareness and develops a threshold model for adoption (assuming that the decision maker utilizes the information obtained in the awareness stage), emphasizing the role of risk considerations in adoption choices. His approach was followed by studies emphasizing the effect of learning in reducing uncertainty (Chatterjee & Eliashberg 1990). Ganesh et al. (1997) capture sequential learning between countries as the use of technology moves across borders. Recent studies focus on the value of referrals from previous adopters (Schmitt et al. 2011) and on the effect of social networks on adoption and abandonment of customers (Goldenberg et al. 2007).

2.1.4. Adoption and increasing return to scale. Much of the traditional literature on adoption assumes that production technology has a decreasing or a constant return to scale and that therefore the technology is produced by a competitive industry. In contrast, Arthur (1994) recognizes that often modern technologies have a strong element of increasing return to scale. For example, industries such as biotech, software, and pharmaceuticals require a large initial investment but have a relatively low variable cost on producing new products. Another source of increasing return to scale is network externalities. The benefits of using the Internet or the telephone generally increase with the number of individuals connected to the network. Increasing return to scale leads to the production and marketing of technologies by monopolistic or oligopolistic industries and implies that adoption decisions may be path dependent. If there are two technologies and the inferior was introduced first and thus has established a strong base, it can eventually dominate. Because such technologies may result in outcomes that are inefficient in the long run, Arthur suggests the use of incentives to support better technologies that may lag in the early stages of introduction. But the capacity of intervention to affect path dependency is limited.

2.1.5. Interdependency and adoption. David (1990) suggests that interdependency among industries may lead to the sequencing of development and the diffusion of new technologies. For example, adoption of certain general-purpose technologies may change the technological path, thereby triggering further technological change. A notable instance was the adoption of electric power instead of mechanical power (steam), resulting in, for example, structural changes in the entire industry and factory location. Majumdar et al. (2010) similarly show that the adoption of broadband for telecommunication is likely to affect the structure of telecommunication industries, to result in the emergence of new industrial applications, and to lead to new paths of technological development. Thus, in the case of major process innovation, the new technology not only replaces an old technology but also alters the evolution of existing industries and leads to the development of more technologies.

[1]An alternative set of five stages according to Rogers (1962) is knowledge, persuasion, decision, implementation, and confirmation, but the interpretation of the stages is similar.

Different modeling frameworks have resulted in different empirical strategies. The imitation model has been frequently estimated by the use of time-series data on aggregate shares of adoption across time and locations. Application of the threshold model took off as micro-level panel data became available; researchers used discrete-choice models such as logit or probit to identify the sources and effects of heterogeneity among adopters. The use of the Tobit model and the Heckman procedure allowed for the estimation of both adoption choices and their intensity. Historical analysis of the spread of technologies across locations allows for the identification of interdependences and the innovation process as well as of patterns consistent with increasing return to scale.

2.2. Adoption in Agriculture and Natural Resources

The large literature on adoption of innovation in agriculture (Feder et al. 1985, Sunding & Zilberman 2001) identifies several crucial factors affecting adoption and provides the starting points for studying agricultural adaptation to external changes. We first review the main findings of the broad literature, followed by findings related to two areas important for adaptation to global changes: conservation technologies and genetically modified (GM) varieties.

Divisible technologies (e.g., new seed varieties) are often gradually adopted as individuals experiment with them and diversify risks. Frequently, new technologies that are embodied in capital goods are initially rented, and purchase decisions are made only after sufficient experiences are accumulated. Intergenerational considerations are important in cases in which older people are less likely to adopt technologies that are embodied with capital goods or that require extra learning, e.g., computers (McWilliams & Zilberman 1996).

A major topic of adoption research is why technologies that seem very beneficial, like energy-conserving technologies, are underadopted.[2] One factor may be lack of access to credit, which may slow the introduction of otherwise profitable technologies. Short-term sharecropping or rental arrangements may also retard adoption of sustainable practices such as terracing. Assessment of modern technologies may entail high cognitive costs (Thaler 1985). Such costs increase the fixed cost of technology assessment and selection and may explain the slow adoption of some conservation technologies (Costanzo et al. 1986). Furthermore, younger people, for example, are more likely to adopt these and other technologies because they have lower cognitive costs and they operate with a longer planning horizon.

There is a large body of research on adoption of conservation technologies in agriculture. Knowler & Bradshaw (2007) survey the literature on adoption of low- or no-tillage practices, which improve soil conditions and sequester carbon, in both developed and developing countries, starting with Ervin & Ervin (1982). The survey of Schoengold & Zilberman (2007) confirms the results of Caswell & Zilberman (1986): Adoption of water-conserving technologies (e.g., drip irrigation) increases input-use efficiency, tends to increase yield, sometimes leads to reduced water intensity, and always leads to reduced drainage. Ward & Pulido-Velazquez (2008) find that adoption of water conservation technologies may increase total water use and may deplete aquifers faster because of expansion of the agricultural land base.

[2]See Wilson & Dowlatabadi (2007) for a survey of alternative explanations.

Regulation, including direct control or rationing, has been used to enhance water conservation in the urban sector. Olmstead & Stavins (2009) suggest that price-based approaches compare favorably with command-and-control approaches in terms of efficiency, monitoring, and enforcement. Linn (2008) shows that financial incentives have a positive effect on adoption of energy conservation technologies but that the elasticity of adoption in response to financial incentives is low. One reason for these findings is the putty-clay nature of capital assets of many industries and the long-term commitments that are associated with adoption of capital goods. Thus, much of the response to financial incentives that lead to the adoption of conservation is by new entrants. One way to promote adoption is to introduce quality standards that set energy efficiency requirements for new products (Geller et al. 2006). The introduction of these quality standards explains why output per unit of energy grew faster in California than in other states.

A key strategy for adaptation to a changing climate is through adopting new crop varieties. Qaim (2009) surveys recent micro-level studies on the adoption of GM varieties and concludes that the yield increases from the adoption of GM varieties are higher in developing countries, where GM traits tend to control pest problems that were not treated previously. However, in developed countries, such varieties frequently replace chemical pesticides, leading mostly to cost reduction while adding environmental benefits. Sexton & Zilberman (2011) find similar results using aggregate data and suggest that the adoption of GM increased the supply of corn, soybeans, and cotton and thus reduced their prices substantially. Qaim (2009) also finds that fast diffusion of GM benefited from the ease of adoption (replacing one kind of seed with another kind) and from nonpecuniary attributes such as improved convenience and increased safety (Marra & Piggott et al. 2006).

2.3. The Role of Information and Marketing

As in the case of climate change, adaptation decisions are often made in environments with uncertainty and learning. The adoption literature in sociology emphasizes the role of informal information exchange, e.g., word of mouth, in inducing adoption. Indeed, econometric evidence shows that such informal exchange between acquaintances and friends provides roughly 50% of the information used by farmers to make economic decisions. Furthermore, the sharing of informal information increases where formal sources of information—e.g., extension, commercial providers (consultants), and media (advertisement)—are less developed (Just et al. 2002). The information cascade literature studies strategic adoption decisions and learning, e.g., incentives of agents to delay adoption in anticipation of learning from other adopters (e.g., Chamley 2004). Zhao (2007) shows that under strategic learning, improved information flow among agents may slow down the early stages of diffusion but speed up the later stages of diffusion after many agents adopt. In addition to learning, social norms and community values are important factors that may affect individual behavior (Akerlof & Kranton 2005). Lynne (1995) shows that social capital and concern about community values can contribute to the adoption of agricultural practices.

Marketing efforts provide information that aims to address issues of uncertainty associated with the purchase of a product, e.g., uncertainties regarding product fit or reliability. Marketers have developed a wide variety of tools (Heiman et al. 2001c)—including product demonstration [both in store and at trade shows (Heiman & Muller 1996)], sampling (Heiman et al. 2001a), money-back guarantees (Heiman et al. 2001b, 2002), warranties, brands, and product support (e.g., tools)—to reduce uncertainty about product reliability. Brands also provide prestige and are more valuable in the context of durable goods than in the context of perishables, such as fruits and vegetables (Jin et al. 2008). Whereas demonstration and sampling reduce ex ante risks and may enhance sales by increasing the expected net benefits of new products or technologies, a money-back guarantee is a put option that protects buyers against mistakes (Heiman et al. 2001c). The value of these tools can be better assessed by recent models of behavioral economics, including those incorporating loss and disappointment aversion (Kahneman 2003).

Experiments have been used to assess marketing strategies and policy tools on adoption. Song & Perry (2009) use a controlled experiment to assess the impact of several promotional tools on adoption. They find that adoption increases when consumers get a direct incentive (e.g., a coupon) and/or an opportunity to learn about experience attributes of a new product. Hayes et al. (1995) use experimental techniques to assess the willingness to pay for safer food and to demonstrate that the extent of such willingness depends on information. Rousu et al. (2007) find that consumer willingness to pay for or experiment with new GM products depends on the characteristics of the product, the consumer's prior belief, and the source of information about the new product. Liu & Huang (2012) rely on experiments to estimate behavioral economic concepts like loss aversion and use such concepts in an econometric analysis of adoption of agricultural biotechnology in China. The desire to have a realistic understanding of technological choices has led to an increased reliance on field experiments, including randomized experiments on the adoption of technologies, especially in the context of development (Duflo et al. 2007). Miguel & Kremer (2004) use randomized experiments to show that, in some cases, institutions such as schools can be used as a mechanism to introduce new practices such as deworming more effectively than incentives to modify individuals' behavior.

2.4. Adoption of Institutional Innovations

Ruttan & Hayami (1984) introduce the notion of institutional innovations (new forms of institutions, management strategies, and policies) and find that they are, to a large extent, induced by resource scarcity, market forces, and new technologies due mostly to increased communication capacities and to advances in the social sciences. Analysis of adoption of institutional innovations by firms follows the same methods as does analysis for the adoption of technological innovation by firms.[3] Adoption of institutional innovation is more challenging when done by the public sector or through collective action. Shiller (2005) suggests that behavioral economics and political science have played a major role in analysis of institutional innovations by public agents. Much of the literature on political economy (e.g., Grossman & Helpman 1994, Rausser et al. 2011) emphasizes the role of the political process in introducing institutional change and shows that such change is not always for the better. Rausser & Zusman (1992) develop a dynamic political economy framework in the context of water resources management, showing that institutional reforms that allocate water more efficiently occur only at moments of crisis. Fischhendler & Zilberman (2005) show that adoption of water trading within the federal water project in California was the outcome of a political process that garnered support

[3]For example, an augmented version of Arthur's (1994) increasing-return-to-scale framework may be useful in assessing the decision by firms as to whether to grow via franchising or via vertical integration.

from multiple interest groups and that such adoption was initiated by a crisis. Brondizio et al. (2009) present conceptual analysis and empirical evidence that both social capital and human capital influence the choice of communal governance institutions that affect economic well-being as well as environmental quality. There is a need for more quantitative analysis of the formation and adoption of institutional innovations.

3. ADAPTATION: AN OVERVIEW

Although the notion of adaptation is generic, our discussion of adaptation and its literature is mostly in the context of global climate change; many of the results presented apply to other adaptation processes. There is no standard definition of adaptation, and it can be viewed from different perspectives. According to the National Research Council (2010a, p. 19), adaptation is an "adjustment in natural or human systems to a new or changing environment that exploits beneficial opportunities or moderates negative effects." A survey of experts (de Franc Doria et al. 2009) concludes that "successful adaptation is any adjustment that reduces the risks associated with climate change, or vulnerability to climate change impacts, to a predetermined level, without compromising economic, social, and environmental sustainability." Some of the distinctions of analysis on adoption can be applied to adaptation.

First, as in the adoption context, it is useful to distinguish between adaptation at the micro level and adaptation at the macro level. Adaptation at the micro level may include selection among discrete strategies such as adoption of technologies that exist elsewhere, migration, and changes in input use with traditional technologies. Adaptation at the macro level may be measured by aggregate behavior, with a distinct feature of policy rule change that is determined at the village, country, or global level.

Second, as with adoption, the adaptation process can be narrowly or broadly defined. An expanded definition of adaptation may view adaptation as a multistage process, and the five stages proposed by Rogers (1962) can, with small tweaking, apply to adaptation. In particular, in the analysis of adaptation to climate change, it is meaningful to distinguish between the stages of awareness [the realization that global warming and greenhouse gas (GHG) emissions occur and linking of the two], interest (the realization that climate change may be harmful and should be addressed by the policy process), evaluation (the climate policy debate conducted at multiple levels), trial (experimentation with various initiatives, e.g., the Kyoto Protocol), and finally adaptation (new institutions, adoption of renewable fuels, changes in crop selections).

In this article, we define adaptation as changes in public and private decision making and resource allocation in expecting or responding to the prospect or reality of large-scale and long-lasting changes. Our definition allows for both proactive and reactive behavior and consists of multiple components, including changes in policy making, institutional and technological innovations, adoption of these innovations and modification of existing practices, and migration. There are several dimensions that differentiate the adaptation processes, and they are discussed below.

3.1. Adaptation Versus Mitigation

Adaptation represents the reduction of both the magnitudes and the impacts of negative changes. The former is often termed mitigation, whereas the latter is often termed adaptation. Mitigation and adaptation can be substitutes if adaptation reduces the need for mitigation

(Kane & Yohe 2000). Tol (2005) and Hof et al. (2009) show that financing investments in the adaptation capacity of developing nations to climate change can reduce the need for mitigation. Adaptation and mitigation can also be complementary, as when mitigation buys time to prepare for adaptation (Parry et al. 2001, Klein et al. 2005, Ingham et al. 2007). Kane & Shogren (2000) investigate how the optimal mix of the two strategies responds to risks.

Kane & Yohe (2000) and Tol (2005) identify the differences between adaptation and mitigation: Whereas many adaptation activities bring private and local benefits, most benefits from mitigation activities have public-good properties and are global in nature, and thus individual nations may underinvest in mitigation. The distinction between the public-good nature of mitigation versus the private-good nature of adaptation is subtle. Some mitigation activities (e.g., reducing GHG emissions through improving energy use efficiency) generate private benefits, whereas some adaptation activities have public benefits. Mendelsohn (2000) distinguishes between private and joint adaptation activities; the latter are public good in nature (e.g., actions that preserve biodiversity). Adger (2003) goes so far as to argue that the most critical social capital for effective adaptation is the ability to solve collective-action problems. Thus, in our view adaptation includes the entire set of activities in response to shocks.

3.2. Incremental Versus Transformative Adaptation

According to Nelson et al. (2007), incremental adaptation utilizes existing technologies and institutional frameworks and is limited in scale. Transformative adaptation goes beyond the existing technologies and institutions and represents major changes in resource allocation across large spatial and temporal scales. The difference between incremental adaptation and transformative adaptation is similar to the distinction between responses at the intensive margin and those at the extensive margin (Guo & Costello 2009). For example, in response to heat waves, moderating electricity use during peak hours is a response at the intensive margin, whereas extensive-margin responses might include building new power plants or adopting new electricity pricing schemes, such as peak-load pricing.

3.3. Modeling Adaptation Within an Equilibrium Versus Within Evolutionary Frameworks

Adaptation is sometimes modeled as a transition from one equilibrium to another in response to a shock, as in studies on the impacts of climate change, e.g., Mendelsohn et al. (1994), Schlenker et al. (2005), and Deschenes & Greenstone (2007). Consequently, the benefits of adaptation are calculated as the difference between the immediate effects of external changes and the long-run effects after the economy reaches the new equilibrium. For instance, Hornbeck (2009) finds that the long-run adjustments to the American Dust Bowl recovered approximately 14–28% of the short-run annual costs. These equilibrium-based studies can also help identify important contributors to successful adaptation, e.g., migration after the American Dust Bowl (Hornbeck 2009) and irrigation in adapting to warmer weather (Schlenker et al. 2005).

Hanemann (2000) argues that equilibrium-based models suffer from significant measurement errors. Furthermore, these studies fail to account for the adjustment costs in the process of adaptation. Quiggin & Horowitz (2003) argue that the costs of climate change are primarily adjustment costs and that, as a result, climate change reduces welfare if the change in climate occurs faster than capital stock adjusts. When temperature changes rapidly, the optimal capital-adjustment speed may be lower than the speed of temperature change, and climate change will unambiguously reduce welfare. Zilberman et al. (2004) argue that constraints on migration and movement across space increase the adjustment cost and reduce the gains from adaptation. Using data from five states in the United States, Kelly et al. (2005) show that, although adapting to climate change could raise the expected agricultural payoffs, the costs of adjustment are three times the expected gains from adaptation. Thus, assuming instantaneous adaptation and ignoring adjustment cost would significantly overestimate the benefit from adaptation.

3.4. Reactive Versus Proactive Adaptation

Historically, most adaptation activities have been reactive (Orlove 2005), i.e., in response to a shock. Climate change offers an opportunity for proactive adaptation: adaptation in anticipation of the major changes predicted by scientists. The timing, manifestation, and impacts of climate change are uncertain, and thus research on proactive adaptation should recognize the role of uncertainty, information, and learning. The real-options approach (Arrow & Fisher 1974, Dixit & Pindyck 1994) provides a convenient framework for studying adaptation to climate change (Zhao 2011). This approach suggests that when adaptation decisions involve sunk investments, an agent has the incentive to wait and gather more information to avoid losses. Information's value lies not only in reducing the likelihood of bad investments but also in enabling earlier actions in undertaking good investments. This value is even higher when agents can learn from each other about the best adaptation choices so that each has the incentive to wait for others to adapt first (Zhao 2007).

Information and learning play critical roles in developing proactive adaptation strategies. Adaptive management of ecosystems provides one example whereby actions are taken not only to maximize social benefits but also to offer more learning opportunities (Marwah & Zhao 2010). Kelly et al. (2005) find that the experience that farmers accumulate from adjusting to changes in weather improves their capacity to address new future climate change. Although information flow is assumed to be exogenous, Kelly et al.'s (2005) model does allow for proactive adaptation.

Because adaptation decisions are mostly local (i.e., involving place-based adaptation), information needs to be tailored to localities. Farmers need better information on a finer scale in making their production decisions (Stern & Easterling 1999), and in urban areas, better local forecasts are needed to prepare for extreme weather events. Two examples of information capacity are the National Integrated Drought Information System and the Regional Drought Early Warning System being developed at the US Drought Portal (**http://www.drought.gov**). Another example is the recent downscaling of efforts to predict future climate change on a much finer scale (Fowler et al. 2007). Resources for the Future is developing a so-called global adaptation atlas, a mapping tool that is tailored to diverse geographical locations throughout the world and that aims to assess the impacts of climate change and to record ongoing adaptation projects (Vajjhala 2009).

4. ADAPTATION STRATEGIES

Early studies on adaptation have been introduced as part of the analyses aimed to estimate the economic impacts of shocks, in particular climate change (Tol 2009). Recent research has produced a range of recommendations for concrete adaptation strategies for various sectors of the economy. For instance, the NRC (2010a) enumerates an extensive list of activities that will prepare different sectors of the US economy to adapt to climate change. Antle & Capalbo (2010) review research on agricultural adaptation to climate change, and Antle (2009) discusses specific vulnerabilities in the US agricultural and food system and the associated adaptation policies. There are many country-specific studies as well.[4] In this section, we discuss several broad categories of adaptation strategies, emphasizing institutions that will facilitate the development and implementation of such strategies.

4.1. Innovation as Adaptation Strategy

The Stern report (Stern 2006) identifies innovative activities as major elements of adaptation to climate change. The large investment in research to develop alternative fuels (Rajagopal et al. 2009) and modes of transportation is motivated partially by the need to adapt to climate change. There is growing debate on geoengineering as an adaptation strategy (Lomborg 2010).

The vast body of economic literature on innovation[5] contains many relevant lessons for adaptation. This literature suggests that innovation induced by economic conditions and policies may arise in response to major environmental and climatic changes. Porter & van der Linde (1995) argue that environmental regulations can encourage innovation and be a source of growth in addition to addressing environmental constraints. But the extent to which the Porter hypothesis is valid is unclear. Rennings (2000) presents a conceptual framework to analyze eco-innovations: innovations that aim to reduce the damage of environmental calamites and the cost of compliance with environmental regulations. He suggests a mix of tools (incentives, standards, command and control) that are the most effective in overcoming underinvestment in eco-innovations given political economic considerations. Olmstead & Rhode (2011) identify and quantify innovative adaptation to changing weather conditions from the progressive movement of agricultural practices over time (for the period from 1839 to 2002) to regions with less favorable climatic conditions.

The literature also has important lessons on factors that may enhance the innovation needed for adaptation. The first lesson is the importance of support for public research and the so-called educational industrial complex, where start-ups and corporations develop and commercialize basic concepts discovered at universities. Although studies in other sectors (e.g., agriculture) have demonstrated the high return to public research (Alston et al. 2009), we are not aware of any economic assessment of the performance of public research or other incentives to induce innovation to adapt to climate change. The second lesson is the importance of designing mechanisms such as patents, prizes, and tax credits to induce innovation activities (Wright 1983, Maurer & Scotchmer 2004). The third lesson is the need for creating institutional arrangements for development of innovations that serve the poor. The limited capacity of the poor to pay for new products is a disincentive for the

[4]Swart et al. (2009) compare country adaptation strategies in the EU, and Osberghaus & Reif (2010) estimate costs of adaptation in the EU. Hedger et al. (2008) and United Nations Framework Convention on Climate Change (2007) provide overviews of adaptation in the context of developing countries. Pollner et al. (2008) study disaster risk management in Europe and Central Asia. Extreme events will be a major challenge associated with climate change, and Boyd & Ibarraran (2009) evaluate the impacts of extreme events and adaptation strategies in Mexico. Downing et al. (1997) and Stringer et al. (2009) discuss adaptation strategies in Africa.

[5]See Stoneman (1995), Sunding & Zilberman (2001), and Lundvall (2010).

private sector to invest in technologies that address the poor's problems. Innovation systems consisting of public/private collaboration have emerged to fill this investment gap in agriculture (Hall et al. 2001). The creation of innovation systems to develop technological solutions that allow the poor to adapt to climate change is likely to be a major challenge. The fourth lesson is the need to optimize regulation of new technologies because regulations often serve as a barrier to innovation (Graff et al. 2009). For instance, the development of technologies and crops that enable adaptation to climate change may be hampered by the existing land use or technology regulations (Sexton et al. 2009).

4.2. Adoption as an Adaptation Strategy

At the heart of the adaptation process, there is a discrete choice among major alternatives, with nesting choices within each one. These types of decisions are in essence adoption decisions, as Feder et al. (1985) and others emphasize. However, whereas the literature on adoption emphasizes decisions regarding new technologies, adaptation studies emphasize adoption decisions mostly regarding existing technologies. This focus on existing technologies is implied in most studies of adaptation to climate in agriculture. Studies that use the Ricardian approach (Mendelsohn et al. 1994) model climate change as a change in weather patterns and assume that adaptation involves farmers adopting the best technology available given the new weather. Similarly, models that simulate the impact of climate change on agriculture assume explicitly that farmers adopt the best technology available (Reilly et al. 2003). The same is true with studies on the impact of climate change on other types of land uses (see the survey by Mendelsohn & Dinar 2009). The same logic also applies to institutional innovations: Once a decision maker realizes that a change occurs and they modify their objective functions, they are likely to consider borrowing, at least in the short run, from existing institutional solutions (possibly from other places). The longer a response time is to a change, especially in the case of proactive adaptation, the more emphasis there will be on introducing new innovations. For example, in the case of climate change, there is emphasis on adoption of alternative fuels, and once such innovations are introduced, then the adaptation process will consist of adoption of these innovations.

4.3. Institutional Adaptation Mechanisms

Institutions often need to adapt to major changes because they may have exacerbated vulnerabilities that triggered the changes in the first place. According to Orlove (2005), institutions that promoted deforestation and overharvesting reduced the ability of societies to cope with climate variability, leading to disastrous impacts, including the collapse of the Maya, the abandonment of Viking settlements in Greenland, and the American Dust Bowl. Miller et al. (1997) suggest that water institutions and laws need to be modified to allow more effective adaptation to the spatial and temporal changes in precipitation distribution that result from climate change.

Agrawal (2008) identifies mechanisms (including incentives and norms) through which local institutions could ameliorate the adverse impacts of climate change. Adger (2003) provides many examples in which the lack of social capital based on trust, reputation, and reciprocity impaired collective-action institutions and contributed to diminished adaptation capacity. Bradshaw et al. (2004) observe that institutional structure contributed to increases in specialized cropping patterns from 1994 to 2002 in the Canadian Prairies, although effective agricultural adaptation to climate change called for diversification. In regions where the use of GM, herbicide-tolerant varieties (e.g., Roundup Ready) is banned and where the adoption of low-tillage practices is thus reduced, vulnerability to soil erosion associated with extreme rainfall will increase (NRC 2010b). Below we discuss two important institutional adaptation strategies emphasized in the literature: risk management institutions and international trade.

4.3.1. Risk management as an adaptation strategy. External changes such as climate change are inherently uncertain events: Their timing, magnitudes, and impacts are random variables. According to NRC (2010a, p. 124), adaptation to such changes, especially if it is proactive, is "fundamentally a risk-management strategy." NRC follows the environmental hazard management literature perspective (Jones 2001) and presents a broad, multistep risk management process in adapting to climate change. The process includes identifying the sources and the nature of the changes, assessing the adverse events and their consequences, communicating the risks to decision makers, and designing and finally implementing specific risk management responses.

Economists have taken a much more focused perspective. Chichilnisky & Heal (1993) argue that there are two responses to climate risks: (*a*) mitigation efforts that reduce the risks and (*b*) insurance that manages risks. Mendelsohn (2006) suggests that crop insurance can be a good adaptation strategy in response to increased weather variability. Pollner et al. (2008) argue that, in response to increased catastrophic risks, governments could resort to the capital markets through pooled insurance coverage (e.g., the Caribbean Catastrophe Risk Insurance Facility) and weather-indexed bonds to securitize these risks (e.g., the indexed catastrophe bond in Mexico supported by the World Bank). These new financial instruments will not only prepare the nations for risk management in the face of climate change but also provide the benefit of a better response to present-day disasters.

There has been extensive research on the theory and practice of insurance and other risk-sharing and trading instruments, including those related to weather events such as weather derivatives (Chichilnisky & Heal 1993, Golden et al. 2007). However, implementation of these tools is challenging for several reasons.

First, the risks are difficult to quantify. Millner et al. (2010) argue that some impacts of climate change are better described by Knightian uncertainties (which cannot be described by a probability distribution) rather than by risks and find that ambiguity aversion could lead to vastly different valuations of the impacts. The difficulty in risk quantification requires innovative approaches to insurance and other risk management tools. For instance, Chichilnisky & Heal (1998) propose a combination of traditional insurance tools and security tools in response to climate change impacts when the extent of the impacts is unknown. In this scheme, individuals purchase insurance policies specific to a particular level of impact and then make bets on the level of climate change impacts using statistical securities.

Second, insurance and other adaptation activities are interdependent (Tol 2009). Availability of insurance may reduce engagement in other proactive adaptation activities; such reduced engagement is a form of a moral hazard. Similarly, increases in the efficiency of other adaptation strategies may reduce the need for insurance. Thus, other adaptation strategies and insurance policies must be designed simultaneously.

Third, the distortion in existing risk management policies could derail their effectiveness as risk management strategies. Agricultural crop insurance programs have encouraged risk-taking behavior (Serra et al. 2005, 2006), and the desire to maintain eligibility for program entitlements discourages farmers from switching to different crops (Anderson 2009). Similarly, Botzen & van den Bergh (2009b) suggests that in the case of flood insurance, a mixture of public and private insurance should be optimal, considering the extreme risk associated with climate change. They find that private-sector insurance leads to increased exposure to risk and that private-sector contribution is needed because of the public-good aspect of insurance.

Fourth, financial devices effective in spreading risks and in reducing the utility losses from adverse events do not necessarily reduce the direct impacts of these events. Capacity in crisis management is needed in addition to financial instruments (see Dilley et al. 2005 and Carreno et al. 2007 for reviews of crisis management strategies).

The assessment of the value of insurance was based on application of an expected-utility approach. However, there is growing evidence that this approach does not capture actual behavior well (Kahneman 2011). Botzen & van den Bergh (2009a) develop alternative behavioral approaches (rank-dependent utility and prospect theory) to estimate the premium that individuals are likely to pay for a reduction in climate change losses, using the example of floods in Holland. The resulting premiums are higher than those under traditional approaches, and therefore the profitability of flood insurance increases. In other words, the use of the behavioral model suggests that the likelihood of adoption of insurance as part of an adaptation strategy is much higher than is implied by traditional models.

4.3.2. International trade as an adaptation strategy. International trade provides risk sharing on a global scale. While in autarky, prices could be significantly affected by domestic changes, and trade helps spread the risks and reduce price volatility. To the extent that different nations or regions in the world face heterogeneous risks of external changes, free trade as an institution can act as a buffer between direct local damages in output (e.g., natural disasters) and indirect losses in utilities (e.g., humanitarian disasters). In this regard, international trade plays a role similar to that of international aid after major disasters. Grada (2007) documents historical evidence that trade facilitated by access has been an important factor in reducing the likelihood and magnitude of famine. Aker (2012) finds an increase in trade in West Africa during drought periods; such an increase ameliorates a drought's impacts. Donaldson (2008) documents the role of railroad access and thus better access to trade in raising rural income and reducing price volatility in rural India. For trade to be effective in helping adaptation, more efficient transportation networks and more accurate detection and warning systems for major changes such as natural disasters are needed.

However, the effects of trade on adaptation are not straightforward. On the one hand, trade may provide an alternative source of supply to regions that suffered from a shock, e.g., drought. On the other hand, trade may divert resources to regions that can pay and make poorer regions more vulnerable to shocks. Fraser (2007) argues that one region's ability to adapt during a food crisis could be hurt by external demands for local food products. More research is needed to identify the aspects of international trade that will promote adaptation. They will likely depend on the specific kind of changes and risks involved, the locations of the changes, and the market imperfections in the affected regions.

There is limited research on the role of trade in preparing nations for climate change. Some assessment models explicitly allow for international trade, especially for agriculture (see, for example, Reilly & Hohman 1993, Reilly et al. 2003, and Nelson et al. 2009), but do not investigate how international trade can be improved to help adaptation. Winkler et al. (2010) provides a framework to analyze how international trade can help adaptation by reducing pricing variations due to weather shocks in isolated production regions.

The trade and environment literature (e.g., Copeland & Taylor 2003) has found that improving property rights on natural resources could be a major step toward building a developing nations' adaptation capacity. But Karp et al. (2001, 2003) use a dynamic framework, specifically the North-South model, to show that international trade is a double-edged sword. It could (*a*) exacerbate the negative impacts of imperfect property rights in the South when resources are overexploited and exported or (*b*) serve as a mechanism for recovery from a natural disaster through imports.

There is some research on how international trade institutions, such as the World Trade Organization (WTO), could be reformed to provide more incentive for nations to reduce their GHG emissions and thus mitigate climate change. Frankel (2008) suggests that recent research has increasingly recognized the limitations of the current WTO rules in inducing nations to collectively commit to reducing their GHG emissions. Hufbauer et al. (2009) review functions of a range of GATT (General Agreement on Tariffs and Trade) articles within the WTO provisions and suggest a range of reform measures to WTO to allow nations to adopt GHG emission policies while keeping their competitive advantages and maintaining the free-trade structure. Karp & Zhao (2009) argue that, although nations might still voluntarily participate in international GHG reduction treaties, WTO rules should be reformed in the long run so that trade measures could be used to enforce GHG reduction treaties.

4.4. Migration as an Adaptation Strategy

Trade, aid, and insurance may ameliorate the negative impacts of shocks that are temporary or limited in scope. However, when the changes are significant and permanent, some of the population may adapt by migrating out. There is evidence that migration has been part of a traumatic adaptation to climate change. As discussed above, Orlove (2005) documents many historical examples, emphasizing the cases of the Maya of Mexico and Central America, the Vikings in Greenland, and the American Dust Bowl. In all these cases, the response to worsening climate conditions was migration, and the process was very costly to the affected individuals.

The global change literature suggests that climate change will lead to mass migration despite the fact that the geographical scales and magnitudes are uncertain (Massey et al. 1993, Myers & Kent 1994, Faist 2000, Myers 2002, McLeman & Smit 2006, Feng et al. 2010). The literature widely discusses the possibility of mass migration due to decreased agricultural productivity, reduced access to clean water, higher frequency of and more severe natural disasters, and rising sea levels (Perch-Nielsen et al. 2008, Laczko & Aghazarm 2009a). Warner et al. (2009) argue that climate change is already causing migration. Reuveny (2007) provides evidence of environmental migration in the past six decades, suggesting that climate change induces significant patterns of migration. Feng et al. (2010) estimate the impacts of agricultural yields on migration from Mexico to the United States and extrapolate the future impacts of climate change on Mexico-US migration through yield effects. Feng et al. estimate that, by the year 2080, 1.4–6.7 million adult Mexicans will have emigrated due to climate change–induced yield losses in Mexico.

Climate change may consist of worsening weather conditions in some regions (e.g., parts of Mexico) and improved weather in other regions (e.g., parts of Canada), and in a world without transaction costs, there may be migration from regions with deteriorating climate to regions with improving climate. However, institutional barriers to relocation may result in a large loss of welfare relative to cases without transaction costs or other constraints (Zilberman et al. 2004). This situation is aggravated by the fact that poor countries tend to be most adversely affected by climate change and lack adaptation capacities. For these countries (the so-called hot spots), large populations might be forced to migrate as a last resort to survive (Warner et al. 2009). Mitigating potential damage from seawater erosion and other climate change–induced disasters will reduce migration. In some cases, deteriorating climate conditions may lead tribes or groups to relocate by invading territories occupied by other groups. Zhang et al. (2007) present quantitatively analyzed historical evidence suggesting that climatic change has led to a cycle of migration wars and price fluctuations. Burke et al. (2009) estimate the likelihood of war and conflicts as well as the number of fatalities resulting from warming in Africa. Specifically, on the basis of future weather predictions, by 2030 climate change will have led to hundreds of thousands of deaths from war and conflict.

Migration can be viewed as adoption of another country, and its drivers may include either push factors (e.g., low income in originating countries) or pull factors (e.g., high income in receiving nations) (Lee 1966). The economics literature emphasizes income and employment differences between originating and receiving countries and models migration as movement from labor-abundant economies to labor-scarce economies (Stark 1991, Massey et al. 1993). Like adoption decisions, social interaction and networks are important determinants of migration choices (Taylor 2010). Economic factors are not the only drivers of migration. Political freedom, religious repression, war, and natural disasters could also lead to major population displacement (Castles & Miller 1998).

In the statistical demography literature, population and population density are major drivers of migration. In a statistical analysis of migration among 11 countries from 1960 to 2004, Cohen et al. (2008) show that migration patterns depend significantly on the differences in population and areas of the originating and destination regions. This mathematical demography approach provides systems and models for population dynamics over space and time; such models could incorporate the impacts of external changes such as climate change and could explicitly model migration as adaptation to these changes.

4.4.1. Patterns of migration. There are varying patterns of migration as an adaptation strategy. Migration patterns are differentiated according to the affected population's demographics (age, income levels), the destinations of migration (domestic or international), and its duration (short or long term). Each migration pattern might prove to be the most appropriate response to a particular kind of external shock. For instance, natural disasters tend to cause short-term displacement of entire populations, whereas the failure of large ecosystems can lead to long-term migration (Laczko & Aghazarm 2009a). Economic drivers, however, tend to cause migration of working-age laborers. Hatton & Williamson (1998) document a pattern of an inverted-U curve in migration: Both poor agrarian and wealthy industrialized nations have low emigration rates, whereas nations in between have higher emigration rates. Clark et al. (2007) also confirm this finding in their econometric analysis of migration to the United States.

Micro-level studies have investigated income and education levels of individual emigrants. Such studies identify cases with both negative selection [when individuals with low income, education, or skill levels tend to emigrate (e.g., Borjas 1987, 2008)] and positive selection of emigrants. Hanson (2010) shows evidence of positive selection in terms of emigrants' education levels. Migration may involve large sunk costs due to long-distance transportation, language barriers, and periods of unemployment in job searches. Those individuals with higher income and skill levels then have a higher capacity to migrate. But when migration is less costly (e.g., in the case of migration to nearby areas), low-income individuals have the highest incentive to migrate.

Although international migration has been the subject of intense debates, most of the migration in history is domestic and is "from economically lagging to leading rural areas" (World Bank 2010). This pattern is especially true when there is significant spatial heterogeneity in economic development within a nation. For international migration, Clark et al. (2007) find that migration to the United States is higher when source countries speak English, are geographically closer to the United States, and already have a large immigrant population in the United States (due to network effects).

4.4.2. Impacts of migration. Migration could have major impacts on salary levels, economic development, and environmental resources. On the positive side, free movement of factors of production contributes to economic growth and human development (de Haas 2009). Contentions about migration arise mainly from the distribution of its impacts. In the country of origin, emigration reduces labor supply, and such a reduction could improve the wage level. Remittances sent home by emigrants could also help local economic development (see, for example, Adger et al. 2002 on coastal communities in Vietnam). However, when skilled laborers emigrate, the resulting brain drain may reduce the wage of unskilled labor and may hurt the sending country's productivity (Wong & Yip 1999, Hanson 2010). In the context of environment-induced migration, emigration relieves the environment in the sending country (Laczko & Aghazarm 2009a, World Bank 2010), potentially allowing the environment there to recover.

For receiving countries, the inflow of immigrants can reduce wage levels, but if there are increasing returns to scale, migration and conglomeration could speed up economic growth (World Bank 2010). Gleditsch et al. (2007) caution that immigration may impose strains on local recourses and cause potential conflicts, but Raleigh et al. (2008) argue that, because most environmentally induced migration is short term and domestic, there is little potential for international conflicts. The main risk lies in domestic conflicts and tensions during periods of environmental stress.

Eventually, the impacts of migration depend critically on its scale. Large-scale labor migration from rural to urban China has tremendously strained the supply of social services, causing transportation bottlenecks and contributing to crime and income inequality. In some regions migration has also resulted in a shortage of farm labor and reduced agricultural productivity (Rozelle et al. 1999). The potential of migration as an adaptation strategy depends critically on the capacity of the receiving regions in handling the massive inflow of immigrants.

4.4.3. Improving adaptation capacities. Although most migration in history has been passive responses to external changes, proactive approaches to migration will be needed for successful adaptation to major shocks such as climate change. The approach requires better predictive models of future migration patterns and early preparations in receiving regions. Döös (1997) argues that, although there is tremendous uncertainty about the impacts of climate change in different regions, models could be developed that predict migration patterns on the basis of reduced food production and rising sea levels.

Institutions play a major role in affecting the volume and destinations of migration, especially internationally. Although international treaties, in general, support the freedom to emigrate, it is up to the receiving countries to decide their policies on immigration. If climate change does lead to major population displacement across borders, immigration laws will need to be reformed in response. For instance, few current immigration laws explicitly allow environmentally induced immigration, as is done in Sweden (Brown 2008).

Martin (2009) presents a set of strategies for managing environment-induced migration for countries at different income levels. Extreme events, such as natural disasters, cause sudden and (usually) short-term displacement and require emergency response capacities, such as humanitarian assistance. Slow changes, such as gradual increases in the temperatures or degradation of ecosystems, leave more options for planned responses. More research is needed—especially for climate change adaptation—to evaluate the population pressure under different scenarios; to identify the possible sources, destinations, and associated scales of migration; and to examine the likely impacts of the migration and institutional responses.

5. CONCLUSIONS AND FURTHER RESEARCH

Adoption is part of the innovation process. Innovations are introduced, raising key questions of who adopts them and when they are adopted. The adoption literature investigates, among other things, patterns of adoption, the profile of adopters, the timing of adoption, the evolution of the technology once adopted, and impacts on other technologies and prices. Adaptation is a response to a shock (e.g., climate change) and consists of many actions, including adoption. Adoption takes place in a myriad of circumstances, whereas adaptation relates to a significant occurrence. The two literatures have much in common, and we conclude that the adaptation literature in particular can gain from the lessons of the adoption literature.

Both the literature on adoption and that on adaptation were developed in other disciplines and were adopted and later adapted by economists. The research on adoption originated in sociology, and its introduction to economics filled a gap and explained behavioral patterns that were overlooked by neoclassical microeconomic models. Adaptation is an essential concept in biology, and although there were several earlier attempts to integrate this idea into economics, now it has become an important element in the economics of climate change. The economic literature on both topics has coevolved with literatures in other disciplines; for example, the adoption literature in economics and that in marketing are closely related, and the economic adaptation literature is evolving within the general climate change literature.

Although the adoption literature has several major thrusts, economists have paid the most attention to the revealed final act of adoption and less attention to the preadoption decision process. Because of the importance of climate change to the adaptation literature, the literature tends to place much emphasis on preadaptation activities. Much of this literature is aimed at designing policies that will reduce the cost of adaptation once climate change events occur. Because of the emphasis on actual adoption behavior, much of the applied adoption models were derived from the threshold and imitation models, quantifying the contributions of profitability, risk consideration, policy and institutional parameters, scale, and socioeconomic and biophysical variables in adoption choices. The adoption literature emphasizes the major features of the threshold model, namely modeling explicitly decision making at the micro level, recognizing heterogeneity of both economic agents and institutions, and quantifying dynamic processes.

More recent studies of adoption focus on five important aspects. First, the features of the technology play a crucial role in shaping the adoption process. In particular, technologies with increasing return to scale have completely different patterns of evolution and adoption compared with traditional technologies with increasing marginal cost. Second, networks are important both in learning as well as in reducing the cost of operation. Third, new behavioral economic models are useful in explaining some patterns that stymie neoclassical models. Behavioral economics is especially effective in improving the modeling of information and learning in economic models. Fourth, there is a growing recognition that path dependency is important and that action in the past sets significant constraints on patterns of adoption. Fifth, understanding adoption in the broader sense, better modeling of learning and assessment before the actual act of adoption, and behavioral modification after adoption are important in having a meaningful picture of adoption and technological change.

Proactive activities have been a major area of emphasis throughout the history of climate change–related adaptation literature. These proactive activities include changes in the decision-making process to adapt to new situations, mitigation activities and policies, and emphasis on strategies like innovation that will allow changes in behavior when crises occur. Studies of responsive adaptation were emphasized in the early research on climate change because of their contribution in assessing the value of proactive and preventive activities like mitigation and innovation. Only recently, as it was realized that some changes in climate are inevitable, has there been increased emphasis on research adaptation for its own sake. Conceptually, adoption-like behavior is an important component of responsive adaptation, as it includes adoption of technologies or institutions, some of which are new and some of which previously existed. Furthermore, migration is essentially an adoption of a new location. We have seen and expect more cross-utilization between the adoption literature and the immigration literature. For instance, the discrete-choice and share models have been used for the econometric estimation of behaviors on adoption choices of individuals and groups. Heterogeneity, risk, and network considerations are likely to be important in both adoption and migration for adaptation.

The literature on adaptation has put much more emphasis on historical evidence than has the adoption literature. One reason is that adoption of new technologies is ubiquitous, whereas extreme events that require adaptation are fewer and require longer periods of time to obtain sufficient evidence. The historical evidence emphasizes that, although responses to shocks have been diverse, migration has tended to increase from regions that are negatively affected by long-lasting and severe shocks. These migration processes are not necessarily smooth and may result in violent conflicts. This historical evidence underscores the need to develop better analysis, institutions, and solutions that will enable effective and peaceful proactive adaptation strategies for likely shocks such as climate change. Such an approach should therefore influence the direction of further research in this area.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

We would like to thank Jean-Paul Chavas, Gordon Rausser, Geoffrey Barrows, Scott Kaplan, and Eunice Kim for their advice and assistance. The authors' research is supported by the Energy Biosciences Institute.

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Annual Review of
Resource Economics

Volume 4, 2012

Contents

Resource Economics

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