ADAPTATION: SENSITIVITY TO NATURAL VARIABILITY, AGENT ASSUMPTIONS AND DYNAMIC CLIMATE CHANGES

STEPHEN H. SCHNEIDER

Department of Biological Sciences, Stanford University, Stanford, California 94305-5020, USA

WILLIAM E. EASTERLING

The Pennsylvania State University, Department of Geography
University Park, Pennsylvania 16802-5011, USA

LINDA O. MEARNS

National Center for Atmospheric Research, Environmental and Societal Impacts Group
PO Box 3000, Boulder, Colorado 80307, USA

Abstract: The role of adaptation in impact assessment and integrated assessment of climate policy is briefly reviewed. Agriculture in the US is taken as exemplary of this issue. Historic studies in which no adaptation is assumed (so-called "dumb farmer") versus farmer-agents blessed with perfect foresight (so-called "clairvoyant farmer") are contrasted, and considered limiting cases as compared to "realistic farmers." What kinds of decision rules such realistic farmer-agents would adopt to deal with climate change involves a range of issues. These include degrees of belief the climate is actually changing, knowledge about how it will change, foresight on how technology is changing, estimation of what will happen in competitive granaries and assumptions about what governmental policies will be in various regions and over time. Clearly, a transparent specification of such agent-based decision rules is essential to model adaptation explicitly in any impact assessment. Moreover, open recognition of the limited set of assumptions contained in any one study of adaptation demands that authors clearly note that each individual study can represent only a fraction of plausible outcomes. A set of calculations using the Erosion Productivity Impact Calculator (EPIC) crop model is offered here as an example of explicit decision rules on adaptive behavior on climate impacts. The model is driven by a $2xCO_2$ regional climate model scenario (from which a "mock" transient scenario was devised) to calculate yield changes for farmer-agents that practice no adaptation, perfect adaptation and 20-year-lagged adaptation, the latter designed to mimic the masking effects of natural variability on farmers' capacity to see how climate is changing. The results reinforce the expectation that the likely effects of natural variability, which would mask a farmer's capacity to detect climate change, is to place the calculated impacts of climate changes in two regions of the US in between that of perfect and no adaptation. Finally, the use of so-called "hedonic" methods (in which land prices in different regions with different current average climates are used to derive implicitly farmers' adaptive responses to hypothesized future climate changes) is briefly reviewed. It is noted that this procedure in which space and time are substituted, amounts to "ergodic economics." Such cross-sectional analyses are static, and thus neglect the dynamics of both climate and societal evolution. Furthermore, such static methods usually consider only a single measure of change (local mean annual temperature), rather than higher moments like climatic variability, diurnal temperature range, etc. These implicit assumptions in ergodic economics make use of such cross-sectional studies limited for applications to integrated assessments of the actual dynamics of adaptive capacity. While all such methods are appropriate for sensitivity analyses and help to define a plausible range of outcomes, none is by itself likely to define the range of plausible adaptive capacities that might emerge in response to climate change scenarios.

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1. Introduction: Non-Adapting Versus Perfectly Adapting Agents

Evaluation of the costs of a given scenario of climatic changes on environment and society (also called "climate damages" in integrated assessments) are needed before attempts can be made to balance the costs of climatic impacts (e.g., crop yield losses) with the costs of mitigation activities (e.g., a carbon tax-induced loss of GDP; e.g., see Nordhaus, 1992). Adaptation to climatic change is an integral component of impact assessments, which, in turn, are an integral component of policy analyses of climatic changes (e.g., Reilly et al., 1996). Many early generation climatic impact assessments (e.g., Schneider and Chen, 1980, one of the first to call for "integrated assessments" — IA) did not explicitly attempt to account for adaptive responses, and thus have been criticized for neglecting adaptation potential (e.g., Yohe, 1990). However, such second generation impact assessments (see, e.g., Schneider (1997) for a review and classification of various generations of integrated assessment models — IAMs) are typically based on smoothly varying climatic change trends, whereas coastal residents (e.g., West and Dowlatabadi, 1998) or farmers (e.g., Kaiser et al., 1993, or Schneider, 1996) in the real world will need to adapt to climatic change trends embedded in a very noisy background of natural climatic variability. Thus, although first generation impact assessments were rightly criticized for neglecting adaptive response (e.g., by Rosenberg, 1992, who first posed the limiting extremes of "dumb" versus "smart" farmers with respect to their adaptive behaviors), most second generation studies have yet to consider the complications to any adaptation strategies implied by both natural variability and nonlinear behavior, i.e., "surprises." Variability can, of course, mask slow trends and thus delay adaptive responses (but see Kolstad et al., 1999). They may also prompt false starts leading to maladaptation. In addition, unforeseen non-linear climatic events can lead to unwarranted complacency.

Moreover, in addition to direct climate effects on yields or flood frequency, there are a host of other changes that adaptive agents — farmers, coastal dwellers or others — need to anticipate in a dynamic world, in which many factors are changing simultaneously, and not necessarily independently. Although we will not directly deal with this issue here, these factors include degrees of belief that the climate is actually changing, knowledge about how it will change, foresight on how technology is changing, estimation of what will happen in competitive granaries and assumptions about what governmental policies will be in various regions and over time. Adaptive behavior to climate change is embedded in the background of shifting market and social conditions, which may render adaptive behavior for future climate change much more multi-faceted than is usually assumed (e.g., Risbey et al., 1999). Clearly, a transparent specification of such agent-based decision rules is essential to model adaptation explicitly in any impact assessment. Moreover, open recognition of the limited set of assumptions contained in any one study of adaptation demands that authors clearly note that each individual study can represent only a fraction of plausible outcomes.

The U.S. Department of Energy (DOE) study managed by David Slade of the DOE and chaired by Roger Revelle (see DOE, 1980) was one of the first organized assessments to recognize the importance of adaptation as a potential response to the advent or prospect of anthropogenic climate change. Three categories of social response were considered (e.g., see Chen, Boulding, Schneider, 1983): mitigation (i.e., cuts in CO_2 emissions), adaptation (e.g., planting better-adapted crop strains) and prevention (e.g., geoengineering). One example of the latter would be a deliberate attempt to counteract the radiative heat trapping effects of greenhouse gases with solar reflecting aerosols (e.g., see *Climatic Change*, vol. 33, no. 3 (1996) for several articles containing wide-ranging discussions of the problems and prospects of geoengineering).

Schneider and Thompson (1985), in an intercomparison of climate change, ozone depletion and acid rain problems, differentiated passive adaptation (e.g., buying more water rights to offset impacts of a drying climate) from "anticipatory" adaptation (e.g., see Smit et al., this issue). They suggested investing as a hedging strategy in a vigorous research and development program for low carbon energy systems *in anticipation* of the possibility of needing to reduce CO_2 emissions in the decades ahead. The idea was that it would be cheaper to switch to systems which were better developed as a result of such anticipatory investments made in advance. Such active (i.e., anticipatory) forms of adaptation (e.g., building a dam a few meters higher in anticipation of an altered future climate) have been prominent in most subsequent formal assessments of anthropogenic climate change (e.g., NAS, 1991). Nearly all modern integrated assessments explicitly (e.g., Rosenberg; 1993, Rosenzweig, Parry, and Fischer, 1994; Reilly, 1996), or implicitly (e.g., Mendelsohn, Nordhaus, and Shaw, 1996) attempt to incorporate (mostly passive) adaptation. While these studies should be applauded for attempting to recognize and quantitatively evaluate the implications of adaptive responses on the impact costs of climate change scenarios, serious problems with data, theory, and method remain. It will be argued that a wide range of assumptions should be part of any attempted quantification of adaptation (e.g., as recommended by Carter et al., 1994). Moreover, when possible, both costs and benefits of climate change scenarios treated by any integrated assessment activity should be presented in the form of statistical distributions based on a wide range of subjective probability estimates of each step in the assessment process (e.g., as advocated by Yohe, 1991; Morgan and Dowlatabadi, 1996; or Schneider, 1997).

For a number of years there has been debate among some agricultural economists (who asserted that modern farmers and their supporting institutions could overcome most plausible climatic change scenarios) and other analysts who countered that such a complete response would require farmers to be aware of the probability distributions of plausible climatic, technological and market conditions, and to be financially and intellectually capable of instant response to this bewildering array of conditions (e.g., see Kaiser et al., 1993; Schneider, 1997, adaptation section, and references therein). The adaptation optimists had simply replaced the unrealistic "dumb farmer" assumption of the past with the equally unrealistic "genius farmer." Yohe (1992), for example, contrasts a "dumb" farmer with a "smart" farmer, noting that it is as inappropriate to analyze the impacts of climate change assuming all "dumb" (i.e., non-adaptive) farmers as it is "to fill a model of the future with 'clairvoyant farmers', who are too smart." Rothman and Robinson (1997, p. 30), in a conceptual synthesis of IA, also contrasted the "dumb farmer" to a "clairvoyant farmer," and, borrowing from Smit et al. (1996), suggest that "the next step in the evolution of IAs is to assume a 'realistic farmer.'" Real farmers, of course, are likely to behave somewhere in between the limiting extremes. Toward the positive side of the spectrum, in developed countries, land grant universities with their research and extension centers continually monitor environmental trends and develop adaptive strategies for farmers, thus providing a passive early warning system. Toward the negative side, in developing countries, problems with agricultural pests, extreme weather events and lack of capital to invest in adaptive strategies and infrastructure will be a serious impediment to reducing climatic impacts on agriculture for a long time (e.g., Kates, Ausubel and Berberian, 1985; Ausubel, 1991), even for a "genius farmer" or one possessed with clairvoyance. And, some issues remain largely uncertain, such as effects of climate changes or other changing trends in market conditions on produce quality.

2. Natural Variability Masks Trends, Delays Adaptation

One of the major differences in estimates of climatic impacts across different studies is how the impact assessment model treats the adaptation of the sector under study (e.g. coastline retreat, agriculture, forestry, etc.). For example, it had often been assumed that agriculture is the most vulnerable economic market sector to climate change. For decades agricultural impacts researchers had calculated potential changes to crop yields from various climate change scenarios, suggesting some regions now too hot would sustain heavy losses from warming whereas others, now too cold, could gain (e.g., see references in Rosenzweig et al., 1994, or Smith and Tirpak, 1988). But Norman Rosenberg (e.g., Rosenberg and Scott, 1994) has long argued that such agricultural impact studies implicitly invoked the "dumb farmer assumption." That is, they neglected the fact that farmers do adapt to changing market, technology and climatic conditions. Agricultural economists (e.g., see Reilly et al., 1996) have argued that such adaptations will dramatically reduce the climate impact costs to market sectors like farming, transportation, coastal protection or energy use. Other types of social scientists and ecologists, however, often dispute this optimism, because it neglects such real world problems as people's resistance to trying unfamiliar practices, problems with new technologies, unexpected pest outbreaks (e.g. Ehrlich, Ehrlich and Daily, 1995), or the high degree of natural variability of weather. The latter will likely mask the slowly evolving human-induced climatic signal and discourage farmers from risking anticipatory adaptation strategies based on climate model projections (Hulme et al., 1999).

Clairvoyant adaptation is seriously challenged by the very noisy nature of the climatic system. It is doubtful, we believe, that those in agriculture or concerned about coastline retreat will invest heavily in order to adapt their practices so as to follow before-the-fact climate model projections, rather than actual events. We can only speculate on whether or not agricultural support institutions, the research establishment particularly, will be influenced by such projections. The high natural variability of climate will likely mask any slowly evolving anthropogenically induced trends — real or forecast. Therefore, adaptations to slowly evolving trends embedded in a noisy background of inherent variability are likely to be delayed by decades behind the slowly evolving global change trends (e.g. Schneider, 1996; Morgan and Dowlatabadi, 1996). Moreover, were agents to mistake background variability for trend or vice versa, the possibility arises of adaptation following the wrong set of climatic cues, setting up a major system malfunction. In particular, agents might be more influenced by regional anomalies of the recent past in projecting future trends, and use the recent past to extrapolate incorrectly long-term trends at a global scale.

It is doubtful that millions of disaggregated decision-makers (farmers in this example) will respond uniformly or quickly to forecasts of global climatic changes and other factors from IAMs. On the other hand, one of the technological adaptations that could mitigate climatic impacts on agriculture is seed development to cope with altered climates. But, there is only a small number of seed companies capable of altering the genetic character of crops and marketing these better-adapted strains on a large scale to farmers (e.g., those in industrialized countries in the Organization for Economic Cooperation and Development (OECD)). Rather than millions of disaggregated decision makers at the farm level, therefore, there may be three or four orders of magnitude smaller numbers of decision-makers. In essence, *the problem in modeling adaptation rests on how to incorporate human behavior via a set of decision rules carried out by representative adaptive agents into the models' structure* (perhaps in menu options) so as to make the models more "actor-oriented." Decision-makers who use results from such later generations of IAMs to help understand about the costs of climate change must be aware of the controversial nature of assumptions about adaptation behavior of various actors that often lurk invisibly in different IA studies. Therefore, it is essential that all authors presenting impact assessments with adaptive behavior implicitly or explicitly included make clear what the behavioral assumptions of the adaptive agents are and how limited those proposed sets of behaviors are relative to a wider range of plausible behaviors that are discussed in the literature (e.g., see Moss and Schneider, 1997).

The case of coastal flooding is a good example of how incorporating climatic variability can significantly reduce the damage reduction potential that adaptive activities might otherwise have offered if climatic change trends were not plagued by very high levels of natural variability. West and Dowlatabadi (1998) devised a set of decision rules by which coastal dwellers would choose to rebuild, remain in place or abandon coastal structures, based on the random occurrence of storm surges superimposed on a slowly rising sea level trend. The "noise" of such random storm surge events substantially alters the adaptability behavior of coastal dwellers relative to those clairvoyant agents whose decision rules do not include the masking effects of climatic variability. (Of course, other masking effects from social uncertainties could arise as well: if new sets of decision rules were imposed by coastal zone planners in the form of set-back requirements or insurance regulators insisting on new actuarial accounting schemes for premium rates, etc.)

2.1. A MODELING EXAMPLE

Kaiser et al. (1993) examined the effect of farm-level adaptations (cultivar selection) lagged ten years behind a series of time-evolving or transient (100-year) climate change scenarios, with an application to a hypothetical southern Minnesota farm. The three climate change scenarios included: Scenario 1 mildly warmer (+2.5°C) and wetter (+10%); Scenario 2 mildly warmer (+2.5°C) and drier (-10%); and Scenario 3 moderately warmer (+4.2°C) and drier (-20%). Kaiser et al. simulated 100-year (1980-2079) trajectories of crop yields and prices (corn, soybeans, and sorghum) relative to 1980 (simulated) yields and prices. Corn production under Scenario 1, continuously adapted to conditions of the previous ten years, yielded about the same as 1980 (no climate change) throughout the 100-year climate change. Corn yields were slightly decreased over time under the Scenario 2 climate change. They were significantly reduced under the Scenario 3 climate change. Kaiser et al. demonstrated that, even when adaptation is lagged behind the time-evolving climate change, it is effective in offsetting some of the deleterious effects of the climate change.

A problem the Kaiser et al. study does not address is the difference between adaptation with perfect knowledge of the changing climate (i.e., instantaneous adaptation as if the farmers were clairvoyant and acting in step with the climate change) and adaptation lagged to represent the masking effect of climate variability on the perceptions of farmers. This potential difference may have policy importance because of the preponderance of extant modeling studies relying on the unrealistic concept of perfect adaptation.

Easterling et al. (submitted) and Mearns et al. (submitted) studied the consequences of using high-resolution climate change scenarios on the modeling of agricultural adaptation in the central Great Plains of the US. Using the EPIC crop model, they demonstrated that perfect adaptation (through changes in cultivar selection and planting dates) to a warmer and wetter climate than present could raise yields above those observed today. Without adaptation, the same crops yielded below current levels. But Easterling et al. (submitted) did not examine what happens when adaptation efforts are not implemented immediately, when they lag behind the climate changes as farmers sort out the signal of climate change from the noise of natural variability. Results of lagged adaptation simulations were not reported in Easterling et al. (submitted).

Building on the study of Easterling et al. (submitted), we now show for the case of Great Plains farmers how natural variability (which masks slowly evolving climatic trends) could affect farmers' capacity to adapt to the advent or prospect of slowly evolving climatic change. Table I shows the percentage difference between simulated corn (maize) yields with current climate and yields for one third, two thirds, and three thirds of $2xCO_2$ climate change from the regional climate model RegCM (Giorgi et al., 1998) with a spatial resolution of 0.5 x 0.5 degrees nested within the CSIRO GCM (Watterson et al., 1995) which has a resolution of 3.2 x 5.6 degrees.

Resource limitations preclude our use of a "true" GCM transient climate change scenario (from the Australian CSIRO GCM) in which to nest the RegCM. Instead, we used an equilibrium climate change scenario based on the radiative forcing equivalent of a doubling of atmospheric carbon dioxide (hereafter, "$2xCO_2$"). We produced a "mock" transient scenario by dividing the simulated $2xCO_2$ equilibrium climate change into one-third segments, where the first third is equal to 33% of the equilibrium change in temperature or precipitation, the second third is 66% and the final third is equal to the $2xCO_2$ equilibrium change. Each of the one-third segments of climate change (temperature and precipitation) was added to the same ten-year baseline observed climate (1983-1992). No change in interannual variability — independent of that caused by simply changing the baseline climate means — was allowed. We assume that it will take approximately 60 years to achieve an equivalent doubling of atmospheric carbon dioxide. Hence, each one-third segment of climate change is assumed to last approximately 20 years. Although the choice of thirds is arbitrary, it allows us to explore qualitatively the transient impacts issue.

The $2xCO_2$ scenario of the RegCM computes average increases in mean daily maximum and minimum growing season temperatures of 5 °C and 5.5 °C respectively above current temperatures for the two cases. Mean growing season precipitation is calculated to increase by about 140%. In contrast, as described above, Kaiser et al. (1993) considered three different climate change scenarios in part based on transient runs of GCMs. Temperature changes evolved slowly along the transient up to the point of $2xCO_2$. However precipitation scenarios were created by linearly increasing and decreasing the percentage changes in precipitation by arbitrary amounts. The third scenario was based on another

GCM run wherein global temperature increased by 4.2 °C by 2060, combined with a linear decrease of precipitation.

The scenario used here is based on an equilibrium $2xCO_2$ GCM run, which resulted in about a 5 °C increase in global average temperature (Giorgi, 1998), and thus is similar to the higher temperature increase scenarios of Kaiser et al. Thus, our scenario may be viewed as a high temperature increase with a somewhat large precipitation increase. Our method of dividing the scenario results into thirds to roughly simulate a transient condition is reasonable only for use in a purely illustrative context. In essence, Kaiser et al. also developed highly arbitrary scenarios by using linear increases or decreases in precipitation changes. We do not imply that our numerical results – nor those of other studies with a high degree of arbitrary and limited assumptions – should be taken literally, of course, but we do believe the contrasts among different adaptive behaviors may be a robust outcome.

Adaptations tested in EPIC include adjustments to planting dates and to crop varietal traits regulating the length of time from germination to physiological maturity. Warmer temperatures allow planting to proceed earlier in the spring, thus avoiding risk of damaging mid-summer heat during the critical reproductive periods. The longer growing season (frost-free period) enables farmers to plant varieties that take longer to reach maturity, which enables longer grain filling periods and thus higher yields. These two adaptations are always simulated together in EPIC.

Table I makes three adaptation assumptions: no adaptation (the "dumb farmer"); perfect adaptation (the "genius farmer" who foresees future climate change trends perfectly and makes adjustments to maximize yields and revenues); and a more lagged adaptation behavior (a "realistic farmer" who, because of the masking effects of climatic noise, waits twenty years — an assumption to represent learning – before acting on the slowly emerging CO_2-induced climatic signal). Lagged adaptation is identical to no adaptation at all in the first third of climate change. This follows from our assumption that the farmer in the lagged adaptation case has not yet detected a credible signal of climate change. Hence the first steps toward adaptation are not invoked until the second third of climate change.

EPIC is a physiologically based crop model that simulates the effects of climate on plant growth processes that regulate economic yield (Williams et al., 1990). EPIC simulations were run at atmospheric carbon dioxide concentration of 340 ppmv (roughly current concentration). Growth processes are computed on a daily time-step at the scale of a single hectare. Climate stresses decrement maximum optimal plant growth until physiological maturity is reached. The model has been prepared to simulate a "typical" hectare on a single farm. Case A on Table I is for a dryland corn farm in Central Iowa and Case B is for a dryland corn farm in South Central Minnesota (similar to the Kaiser et al., 1993 study).

TABLE I

Dryland Corn. Percentage Differences between Yields Simulated with Baseline Observed Climate (1984-1993) and Yields Simulated with 1/3, 2/3 and 3/3 of $2xCO_2$ Climate Change for Three Levels of Adaptation: (1) No Adaptation, (2) Perfect Adaptation, (3) Adaptation Lagged 20 Years behind Climate Changes.

A. Central Iowa

Climate Change (RegCM)	No Adaptation (%)	Perfect Adaptation (%)	Lagged Adaptation (%)
1/3 of $2xCO_2$	-3	2	-3
2/3 of $2xCO_2$	-8	2	2
3/3 of $2xCO_2$	-17	-0.3	-3
Mean of Thirds	-10	1	-1

B. South Central Minnesota

Climate Change (RegCM)	No Adaptation (%)	Perfect Adaptation (%)	Lagged Adaptation (%)
1/3 of $2xCO_2$	8	13	8
2/3 of $2xCO_2$	12	23	17
3/3 of $2xCO_2$	10	24	22
Mean of Thirds	10	20	16

Note that in all cases on Table I, perfect adaptation to climate change – as we would of course expect — always improves the yield change relative to no adaptation. Moreover, as argued earlier, lagged adaptation, which is intended to simulate crudely the masking effects of natural variability on farmers' perceptions of climatic trends, also reduces the yield changes from the various CO_2-induced climate change scenarios relative to perfect adaptation. As noted above, delayed adaptation in the first third of climate change is synonymous with no adaptation — i.e., farmers have not yet recognized climate change and thus see no reason to change planting dates or crop varieties (Table I). However, delayed adaptation always represents an improvement over the no adaptation cases in the two- and three-thirds of climate change (Table I). In Central Iowa (Table IA), delayed adaptation with two-thirds of climate change raises yields slightly above the baseline (+2%) but then loses ground to the baseline (-3%) with three-thirds. In South Central Minnesota (Table IB), delayed adaptation spurs yields upward relative to baseline yields through the second (+17%) and third thirds (+22%) of climate change.

These results reflect two different experiences with delayed adaptation. In Central Iowa, the adaptations calibrated to the first third of climate change are potent enough to bracket the second third also, leaving a small gain over the baseline after two-thirds of climate change. This is consistent with the finding by Kaiser et al. (1993) that corn yields may thrive with mild climate change even when adaptation lags behind the contemporary climate. In this case, the farmer is not penalized for lack of clairvoyance. But the severity of the final third of climate change overwhelms the adaptations calibrated to the second third. On balance (mean of thirds), lagged adaptation leads to a small loss of yield relative to the baseline while perfect adaptation leads to a small gain. This finding is also consistent with findings by Kaiser et al. (1993) that more severe climate changes erode the effectiveness of lagged adaptations, gradually leading to yield declines relative to the no climate change case

In South Central Minnesota, the climate changes progressively favor maize yields throughout the three one-third increments of climate change. Here, lagged adaptation simply holds yield increases to consistently smaller gains than perfect adaptation. Although we have stressed that the specific numbers on Table I should be viewed only as model-dependent results, the relative differences for the alternative decision rules representing the various degrees of adaptation are likely to be more robust across different models, for different crops and for different locations. (Of course, as noted in the introduction, we do not claim that these climate scenarios used to drive EPIC capture all the higher moments of climate change associated with a true dynamical transient run, nor can they anticipate the possibility of abrupt changes not simulated by current generations of climate models, nor do they anticipate changing market conditions due to technological innovations, climatic impacts in other regions or governmental policies.)

Thus, we believe that future impact assessment activities need to focus on finding as realistic a set of decision rules for adaptation agents as can be posited and supported, which would be aided by including psychologists anthropologists, sociologists, etc., in teams formulating adaptive agent behaviors. Furthermore, all such studies should explicitly perform sensitivity analyses (like those in Table I) using a range of plausible adaptation strategies. For example, a more realistic set of future adaptation rules could have farmers adapt to a scenario of a smooth climatic trend embedded in a realistic, stochastically-varying weather noise background in which the farmer-adapter places greater weights on the yields of the recent past years in choosing future cropping strategies (see, e.g., Yohe, 1992, which is an early attempt at probabilistic analyses of adaptation decisions, though not in the context of climatic noise). Another case could include scenarios of abrupt climatic changes with and without the added complication of natural variability, which itself could change with climate change. As such cases build up in the literature, it will be easier for impact assessors to provide a fuller range of plausible adaptive responses than is available now.

Finally, the "bottom-up" approach we have attempted (in which we explicitly model farmer decisions to adapt their practices based on their perceptions of time-evolving climatic changes) suffers from the difficulty encountered by any process-based modeling technique: trying to aggregate all the complex factors that govern real decision makers into a few simple, explicit decision rules. An alternative approach to such bottom-up modeling would be to search for "top-down" relationships which implicitly aggregate the complexity of farmers decisions into already measured behaviors (e.g., see Root and Schneider, 1995, for citations and a general discussion of scaling issues involved in cycling between top-down and bottom-up approaches). Indeed, some (e.g., Mendelsohn et al., 1996, 2000) have argued that cross-sectional analyses can estimate empirically the adaptation responses of real farmers to differences in climate. Schneider (1997) — from which the next section is based — has critiqued the use of such cross-sectional analyses when applied to modeling adaptive responses to future climate change scenarios, unless (as detailed next) these analyses can be shown to satisfy three assumptions implicit in this top-down technique.

3. "Ergodic Economics:" Limitations in the Applicability of Static Cross-Sectional Methods for Estimating Adaptation Behavior

In addition to underlying assumptions about adaptation determining to a large degree the impacts that specific climatic change scenarios are predicted to have on agriculture, coastlines or forestry, the many interacting factors across connected physical, biological, and social sub-components of the Earth System — the combination of which are the focus of IA modeling — present a daunting challenge. Therefore, some analysts (e.g. Mendelsohn, Nordhaus and Shaw, 1996) have suggested a shortcut around the attempt to explicitly model the salient complex interacting processes by trying to learn from the system itself and to extrapolate aggregate relationships from the past to try to answer the question of how it would respond to future climate change (e.g., how yields would change, adaptation responses, etc.). Climatic model simulations for CO_2-induced climate changes are used to determine regional annual temperature and precipitation changes, which are combined with sectoral information for agriculture, forestry, coastal resources, energy and tourism, via sets of sectoral and "bottom-up" climate-response functions to calculate market damages for each of nearly 200 countries (Mendelsohn, et al., 2000). Numerical values of these damages (often net market benefits in cold regions and net costs in warm places) are given in tables with two or more significant figures. Some of the response functions, which determine the "answers," are based on cross-sectional studies. These derive how firms and people adjust their behavior to accommodate local climate by examining climate differences for the present in different places as a proxy for climate changes in one place over time. A separate response function is estimated for agriculture, forestry, coastal resources, commercial energy, residential energy, and tourism. The effect of a temperature change in the response function depends on the initial temperature. Mendelsohn et al. (2000) note that if a country begins with a cool temperature, a slight warming will result in benefits, whereas if a country begins with a warm temperature, increased warming often is harmful. The response functions describe net revenue in each sector given climatic and economic conditions

Schneider (1997) argued that what is at most problematic in the application of cross-sectional methods is not the results, but the likelihood that many users of these results may not be aware of the many fundamental assumptions invoked both implicitly and explicitly by the use of these techniques (the so-called "hedonic" method). These assumptions are neither universally lauded (e.g. Ayres, 1992), nor always transparent. It is clear, however, that plausible alternative assumptions could radically change the "answers."

Rather than account explicitly via a process-based systems model for complex, coupled physical, biological, and social dynamics that determine the profitability of agriculture or forestry, the hedonic method simply compares these bio-economic activities in warm places like the U.S. Southeast and colder places like the Northeast. This spatial difference in climate provides a proxy for how temperature changes in each place might affect these segments of the bio-economy. The method when applied to this problem is controversial (e.g., Darwin, 1999, and Adams, 1999). For example, natural scientists often dispute that the difference between business as usual in northern climates or southern climates (i.e., two different regions) can act as a proxy of impacts in one region from time-evolving or transient changes in temperature and other variables, to say nothing about surprises. In essence, these methods assume a perfect substitutability for changes at one place over time with changes across space at the same time — a debatable assumption that is tantamount to the *ergodic hypothesis* in mathematical statistics.

A system is "ergodic" if an ensemble of replicates averaged at one instant of time produces the same statistical results as an infinite time average of one member of the ensemble. In statistical mechanics this would mean that an infinite time average of the varying speed of one molecule in an isolated enclosure produced the same value (of kinetic temperature) as the instantaneous average of all the molecules in the container. "Time and space" in this example are, in essence, substitutable — the system is ergodic. Of course, this result will occur only if the system has a unique steady-state response to any exogenous forcing. In other words, an ergodic system's single equilibrium state has no memory of its evolutionary path, only its boundary conditions; i.e., it is a "transitive" system (e.g., Lorenz, 1968, 1970).

The basic rationale for what Schneider (1997) by analogy called "ergodic economics," is that process-based simulation models, no matter how complex are, nonetheless, still very "dumb" relative to real natural/social systems. Therefore, using the logic of Mendelsohn, Nordhaus, and Shaw (1996), why not let the actual system reveal its sensitivities/preferences and adaptive potential over time to global change disturbances in one place by empirically determining how the real world has responded to "global-change-like" disturbances at one time in different places. However, the reliability of the hedonic method rests on three quite fundamental assumptions that need to be explicit in the minds of potential users of the results before they let this method provide policy advice on the viability of adaptation, for instance. The three assumptions, which are analogous to those for the ergodic theorem, are:

1. *Ergodic Economic Substitutability.* Variations over time and space are equivalent (e.g., long-term averaged climate and/or economic differences between two separate places are equivalent to changes of comparable magnitude occurring over time in one place). The underlying process governing a systems' response to disturbances cause transient pathways which may not resemble the equilibrium response to that disturbance. Thus, when cross-sectional models are derived from a system in equilibrium, it is implicitly assumed that the processes which govern transient behavior have been fully captured in that cross-sectional structure.

2. *Transitivity.* Only one steady state occurs per set of exogenous conditions (i.e., the same path-independent, long-term impacts occur for all possible transient scenarios). In other words, surprises and synergisms, which are non-linear and likely to depend on the path of system changes, pose no qualitative threats to credibility of the cross-sectional results. Although non-linearity and "surprises" do not necessarily imply intransitivity (i.e., multiple equilibria), they certainly alter transient responses, and cross-sectional analyses are usually based on current equilibrium conditions whereas global changes over decades will be a transient condition (see point 1 above), with or without the added complication of intransitivity.

3. *Higher Moments Are Invariant.* A primary variable used in cross-sectional analyses to compare two separate regions climatically is annually averaged surface temperature. Thus, a 5 °C difference across two spatial areas is used to predict a response to a 5 °C warming occurring over time at the colder area. This modulus of difference, annual mean surface temperature, may not be a good proxy for actual climatic changes occurring either in equilibrium or over time because annual means do not capture all higher moments such as daily or sea-

sonal cycles or variability (see, e.g. Mearns et al., 1984, or Overpeck et al., 1992). The latter is a paleo-climatic example of "no-analog" climate conditions in which transients and non-invariant higher moments occurred in reality. For example, if much of the anthropogenic warming occurred at night (as some climate models project), this could have very different ecological or agricultural impacts than if there were no change in the diurnal cycle. Or, if seasonality were altered, then even the same annual mean surface air temperature difference today across space would likely be a poor analogy for the impact either in equilibrium or over time for a future climate change that included altered seasonality. Or, if between now and a specified future time, precipitation increased by ten percent, but more than half this annually averaged increase were distributed in the top decile of rainfall intensity (as it has in the US since 1910 (Karl and Knight, 1998)), then using annual precipitation (let alone just annual temperature) difference between two regions today as a proxy for the impacts of a ten percent precipitation increase in the future in the drier location could well be a very poor representation of what would happen, even given the same annually averaged difference.

Clearly, these three assumptions for "ergodic economics" are not valid for many IA applications. But the point here is not to dispute the conclusions published to date based on hedonic methods, only to highlight the implicit assumptions. More specifically, a frequent finding with the hedonic method, as already noted, is that more heat will make already hot places poorer and currently cold places richer. Countries like Canada win and India lose — a sort of "neo-climatic determinism" reminiscent of that espoused at Yale University by Ellsworth Huntington eighty years ago. Mendelsohn and colleagues have wisely acknowledged that even if their results did suggest that the richer countries with big economies and colder locations win more economically than poorer countries that typically are in hot climates lose, this still represents an impact since the distribution of changes is not uniform across income groups. Distributional effects of climatic change are a non-market impact in and of itself — with one "numeraire" for climate damage being the distributional consequence (e.g., see Schneider, Kuntz-Duriseti and Azar (submitted)). Such a distributional impact is not a conflict-free scenario, particularly since the standard economic evaluation (so-called willingness-to-pay) for the "value" of a statistical human life in rich countries is ten or more times greater than for citizens of poor countries.

None of the concerns raised in this section is designed to suggest that it is inappropriate to include static, cross-sectional methods in the spectrum of other partially integrated assessment techniques that currently inform the policy debate. On the contrary, they help to develop one's intuition about possible market-variable impacts of certain climate changes under specified assumptions. The purpose here is to exemplify the critical need for producers and users of any IA products in which adaptation behavior is explicitly or implicitly included to open and conclude their presentations with clear statements about the assumptions and uncertainties in the methods and conclusions, and not to overload the presentation with stand-alone, caveat-free, multi-decimal place tables or results that can be easily overinterpreted by uninformed users. Elsewhere (e.g. Schneider, 1997) it is argued that, at the least, ranges — as in Table I — or, better, probability distributions (e.g., Nordhaus, 1994; Morgan and Dowlatabadi, 1996; Moss and Schneider, 1997; Roughgarden and Schneider 1999), are more faithful representations of the insights that might be more properly drawn from most IAMs, than are several significant figure entries in "best guess" tables. We regret that preparing a subjective probabilistic analysis of adaptive potential, even one limited to the two case study areas we show on Table I, is beyond the scope of this study, because it would involve at the outset a probabilistic treatment of various parameters in several models as well as a broader range of climate scenarios driven by a wide range of emission scenarios. At best, teams of assessment authors examining the available literature could produce subjective probability estimates via formal decision analytic elicitations. As far as we are aware now, such an exercise is currently not even contemplated.

4. Conclusions

We agree with the substantial body of literature that contends adaptation strategies can significantly affect (and usually, but not always, reduce) climate damages that would occur without any adaptive response (e.g., in agriculture or coastal retreat). But we add that perfect adaptation by agents with perfect foresight of slowly and smoothly occurring climatic trends is an unrealistic exaggeration of more likely realistic adaptive responses. In particular, adaptation responses to climatic change will likely be delayed on the order of decades (even for smoothly varying, "surprise free" climatic change scenarios) by the noise of inherent natural climatic variability, which masks slowly changing trends on the timeframe of decades. A set of calculations using the EPIC model is offered here as an example of explicit decision rules on adaptive behavior on climate impacts. The model is driven by a 2xCO_2 scenario from a regional climate model to calculate yield changes for farmer-agents that practice no adaptation, perfect adaptation and 20-year lagged adaptation — the latter designed to mimic the masking effects of natural variability on farmers' capacity to see how climate is changing. The results show that the likely effects of natural variability, which would mask a farmer's capacity to detect climate change, is to place the calculated impacts of climate changes in two regions of the US in between that of perfect and no adaptation. Moreover, if there are non-linearities or climatic anomalies that mask or counter slowly evolving long-term trends, this situation could even lead to maladaptations in response to recent events that are not predictive of the slowly evolving underlying trend. Under such conditions it is possible that realistic adaptation behaviors under a variable environment might not actually fall between the perfect and no-adaptation limits, a point we cannot address quantitatively with our essentially static (i.e., $2xCO_2$) climate change scenarios. Neither can we address the possibility of much greater than $2xCO_2$ climate scenarios, which are very likely if anything resembling "business as usual" (i.e., IPCC, 1996) emissions occurred.

Furthermore, we argue that in addition to the problems of climatic or other sources of noise there can also be systematic effects (e.g., changing market conditions) that complicate design and validation in bottom-up modeling of adaptive agents' decision rules. We caution that those who attempt to circumvent these problems with bottom-up approaches by pursuing top-down techniques like cross-sectional analyses also will encounter additional limitations. Static cross-sectional methods suffer from implicit assumptions that limit their fidelity to simulate actual adaptive behaviors. These implicit assumptions, what Schneider (1997) labeled "ergodic economics," include: (a) equilibrium and transient responses to climatic disturbances are similar; (b) transitive responses (i.e., no multiple equilibria) characterize the system from which cross-sectional models were derived, and (c) future climatic changes can be characterized simply by a lower-order moment of change (typically annual mean temperature difference) and that higher-order moments (e.g., diurnal or seasonal cycles or variances) will be unchanged in future disturbed climates. Such implicit assumptions are unlikely to be appropriate for many climate change applications. For all of these reasons, we recommend that all impact assessments show the sensitivity of their results to a range of plausible adaptation decision rules assumptions, and that each case study should attempt to explore the likelihood of various degrees of adaptation for the regional sector being considered.

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