IRREVERSIBILITY, UNCERTAINTY, AND LEARNING: PORTRAITS OF ADAPTATION TO LONG-TERM CLIMATE CHANGE

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Abstract. The usefulness of adaptation strategies to changing climate depends on the characteristics of the system that must adapt. Divergent views on whether climate change will seriously affect society and what society can do about it can be traced, in part, to divergent views on these characteristics of systems. Issues of scale and how impacts are measured are also important. We identify a set of fundamental characteristics of natural systems and social systems that help to make underlying assumptions in climate change adaptation studies explicit. These are: Short-run autonomous flexibility; short-run non-autonomous flexibility; knowledge and capacity to undertake short-run actions; long-run autonomous flexibility; long-run non-autonomous flexibility; and knowledge and capacity to plan for and undertake adaptations that require changes in long-lived assets. Applications to crop agriculture and ecosystems illustrate how these portraits can be used. We find that if empirical research is to resolve questions of adaptability, more careful specification of the exact measure of impact and far richer models of the process of adaptation, able to test implicit assumptions in much of the existing empirical research, are needed.

1. Introduction

Potential economic and social impacts of climate change have been some of the more contentious analytical problems in the climate change debate. In part, this stems from the lack of predictability of climate change. Equally important, however, have been fundamentally different views about how people are likely to respond to climate change. At one extreme, response has been characterized as the "dumb farmer" where the agent persists in an economic behavior over the course of 100 years or more that is revealed to be increasingly maladapted. At the other extreme, agents are characterized as adjusting to climate change with foresight that eludes our current ability to forecast weather events accurately a few days into the future.

Social science perspectives on adaptation and adaptability span a wide range. One perspective from cultural anthropology portray opposing views on adaptability as cultural "myths." In this interpretation, different "myths" give rise

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to different views about whether earth systems are resilient or fragile and related views on whether hierarchical or decentralized approaches for controlling risks will be effective (e.g. Ausubel et al. 1992; Schwarz and Thompson, 1990). Another related set of work is adaptative management of complex systems, drawn from observations of efforts to manage ecosystems (Holling, 1986; Carl and Holling, 1990). This body of work notes the potential for surprise and unintended consequences in complex systems. It finds a need for scaled back expectations with regard to our ability to "manage" these systems and for management strategies themselves to adapt over time. In economics, the more complex models of decisionmaking involve decisions under continuing uncertainty when irreversibilities (sunk costs) exist (e.g. Pindyck, 1999; Schimmelpfennig, 1995). These models seek to describe the effects of uncertainty on the timing of decisions. Other work in economics is based on the idea that people may prefer less to more risky situations even when the expected value of the outcome is the same. One such application examined how risk preferences would affect the choice of crop to grow if climate became more variable (Yohe, 1992). Other work has assumed that expectations lag the change in climate (Kaiser, et al. 1993) or more recently that agents update their expectations on climate through a Bayesian learning process where the noise of climate variability makes it difficult to detect the signal of climate change (Kelly, et al. 1997).

Our perspective is that social science research might hope to cast different views on adaptation as testable hypotheses that can be investigated through analytical and empirical means. Such a research agenda might resolve the extent to and conditions under which adaptation is easy and costless versus those under which it is difficult, costly, and disruptive. A main goal of this paper is to conceptually lay out the nature of the research needed to resolve some of this debate. We show that the different views about the ease of adaptation stem from subtle differences in assumptions about the characteristics of the system that must be adapted to the changing climate. While some of the research cited above have explored more complex aspects of adaptation and adjustment for some sites, most empirical research on climate change impacts is based on methods and data where at least some of the hypotheses about adaptive capacity are maintained rather than tested. In many cases, the maintained assumptions go little beyond the "dumb" versus "clairvoyant" farmer. As a result, different researchers with different maintained hypotheses use different methods that generate different results. Getting impacts "right" is important if we are to understand the benefits of mitigation—i.e. reducing the emissions of greenhouse gases and thereby slowing or stabilizing the atmospheric concentrations of these gases as is called for in the Framework Convention on Climate Change. Hence, testing these maintained hypotheses—and as a first step making them explicit—is important.

Social science might also hope to provide guidance on what might be done to foster adaptation, reduce vulnerability, and improve resilience to climate change.

Indeed this is a major goal of the ongoing US National Assessment. Here too, the debate can be as equally naïve as the "dumb" versus "clairvoyant" farmer characterization. Some would hope to identify specific technologies or scripts to follow that would guide agents to success under a changed climate (develop a drought resistant crop, estimate the right height for a sea-wall or when to abandon coastal property, or design a dam to meet predicted changes in water run-off). Others see no need to actively consider adaptation strategies at all, believing that our experience with normal climate variability has prepared us well to deal with anything that climate change will bring. We show that the extent to which different strategies for fostering adaptation are useful depends on the characteristics of the system that must adapt. Thus, evaluating characteristics of the systems that must adapt as hypotheses (rather than maintaining them as assumptions) is critical to determining what strategies for fostering adaptation, if any, would be useful.

2. Issues and Definitions

It is useful to clarify some issues and terms before laying out our schema. First, we interpret adaptation as a response that improves the outcome. Our intention is to compare the post-adaptive outcome relative to the outcome with climate change but without the adaptation (a comparison of the two hypothetical states). The post-adaptation outcome may be better, worse, or no different than the situation before the climate changed. Some literatures compare the outcome with adaptation to the pre-climate change outcome (i.e. current conditions) or to a hypothetical future without climate change. In either of these cases, successful adaptation is sometimes taken to mean eliminating all loss so that the status quo situation is retained. Further, some studies only consider adaptation as a response to a loss. We do not exclude the possibility that agents may seek to improve the outcome further through adaptation even if climate change is initially beneficial.,

As we have defined it, adaptation always improves the outcome. There are clearly many ways that agents may respond that worsen the effects of climate change. Just a few examples: Changing comparative advantage in agriculture could cause countries to erect trade barriers that raise the cost of food to the country. Coastal communities may erect coastal protection systems that worsen beach erosion or where retreat from the shore is the preferred option given continuing sea-level rise. Farmers may install irrigation systems only to find that water resources disappear or water becomes too expensive to use. We recognize these "maladaptations" as part of the impact of climate change that agent managing the system seeks to overcome or offset through adaptation. This is one way to define adaptation so that it can be separated from "impact." In much of the writing on adaptation the line between impact and adaptation is only implicit.

Second, almost all discussions about climate change impacts must confront the

issue of scale. Does the analysis concern the ability of the world to feed itself, the extent to which a particular country's coastal resource are threatened, the ability of the individual farmer to prosper, or the success of specific heating and cooling systems? Our view is that the correct scale of analysis depends on the client of the research. While global change generally requires a consideration of the global forces set in motion by the change, the specific affected system of concern will vary depending on the client. Clients might include the Conference of the Parties to the Framework Convention on Climate Change; a national government agency with the power to create or enforce nationwide laws and programs; a local government with responsibility for managing water, land or coastal resources; or the individual farmer, firm or household?

Third, our interest in this paper is in laying out the basic conceptual issues that arise in evaluating adaptation potential, rather than empirically assessing adaptation potential., We cite some empirical examples to help demonstrate our schema and speculate on where they fit within it, but it is not our intention that these speculations are currently proven or without controversy. As noted above, our interest is in understanding what is involved in resolving the existing controversies about potential impacts. Empirical evaluation would require concrete identification of the system to be analyzed, a measure of performance, and alternative formulations of the system representing different adaptive strategies.

Fourth, we use the general term "system" as that thing which must be adapted. It may be, for example, a farm, an economic sector, or a particular strip of coast. How one defines the affected "system" will affect how one defines its characteristics. It is almost certainly correct for a national policymaker to see changes in production and consumption of agricultural commodities that occur in response to changing prices as autonomous, happening without any conscious action by the policy maker. On the other hand, the decision of what to produce and when to sell in response to commodity price changes is typically a very conscious choice of the individual farmer. Whether adaptation to price changes is "autonomous" or not thus depends on whether the system is defined as a national (or world) commodity market or a specific farm.

The concrete definition of the system depends, in our view, on the client for or purpose of the research. To usefully apply the concepts we develop, or to generally conduct useful research on adaptation to climate change, one must clearly identify the decision that awaits action and the first step in this is to identify the client for the research. Adaptation, in our view, is fundamentally about deciding to do something differently. Suppose our job was that of an agricultural extension agent who must advise farmer Jones on how to minimize economic losses (or maximize gains) through decisions made at a particular point in time (e.g. the present, 2050, 2100) that could result from climate change? The "system" is then the combination of resources that farmer Jones manages—the land, inputs, money, machinery, and Jones' education and intellectual ability at the time at which the decision is being

made. The headquarters of an national agriculture department, in contrast, has responsibility to manage the agricultural sector using broader policy mechanisms at its disposal given legislative authorities and constraints under which it operates. If our job is to advise this client, the system is the entire agricultural sector and possible adaptations are those policy mechanisms over which it has authority or for which it could seek authority.

We use the term "autonomous" adaptation as a response that occurs without conscious decision by the agent. We are interested in the existence of autonomous adaptation because it affects the actions of the agent. For example, farmer Jones' interest in whether (s)he must do something consciously as a result of climate change—adopt a new cultivar perhaps—depends on whether the system in which (s)he operates will adjust without his conscious intervention If Jones' local seed salesman is evaluating cultivars and making recommendations for what does well in the local area then Jones' decision will be based on the overall performance of new cultivars. (S)he need not consciously recognize that the cultivar of choice performs well, in part, because climate has changed—Jones' system will autonomously adapt to changing climate. The situation could be quite different for farmer Smith who saves some of his crop for seed year-after-year—Smith will need to consciously recognize that the variety is becoming increasingly maladapted and seek out a variety that performs better.

Fifth, our focus is primarily on human response to climate change and human intervention to foster adaptation. In many cases, weather and climate do not affect people directly but indirectly affects them through effects on physical/biological systems. Thus, if there are adaptive mechanisms in these systems that operate without human intervention (e.g. species migrate or adapt) it is important that agents seeking to use and/or manage these systems include this "autonomous" adaptation in evaluating the system they are managing. For our focus on agent decisionmaking, the adaptive responses of natural systems that occur without human intervention aimed at causing the response are, by definition, autonomous. Again, we speculate about natural system adaptation in some of the examples we provide because it is of interest to human agents who might want to intervene.

Finally, we use the term system "portraits" to describe combinations of characteristics that describe differences in systems. We use the term portrait in the sense that a portrait is a representation, not reality itself. Given the level of abstraction, the reader may prefer to think of these as caricatures or sketches. Understanding the elements of these portraits illustrate the conditions under which, for example, either warming or cooling can generate damages; when the rate of climate change matters; the potential effectiveness of R&D to reduce damages; and whether improved climate forecasting or better weather and climate data will reduce damages. The results suggest how greater adaptability and resilience to potential climate change can be fostered depending on which portrait best represents a system. We conclude with some concrete examples of different systems, including;

crop agriculture, forest and biodiversity loss, water reservoir and flood control, coastal property, and outdoor recreation, to illustrate how these different portraits are more or less applicable to different situations. Again, our empirical examples are meant to be illustrative rather than conclusive.

3. A Framework

There are widely divergent views on whether climate change will seriously affect society and what society can do about it. It is our premise that those views stem from more fundamental characteristics about society's interaction with climate that could, in principle, be evaluated. We identify these characteristics in a simple table to illustrate the range of divergent implications that stem from different combinations of them. Identifying those fundamental characteristics provides a guide to organizing research to evaluate effects of climate change while making underlying assumptions explicit. The system characteristics we identify are: Whether the adaptation response of the system is autonomous or requires conscious recognition by a human agent that climate has changed and conscious action by the agent to change the system to reduce losses. Whether there are irreversibilities (fixed costs) associated with adaptive actions that reduce flexibility to adapt in the short run. We recognize an additional characteristic of the agent who manages the system: whether the agent knows what adaptive action to take (and has the capacity to undertake it). Inherent in knowing what adaptation to undertake is the problem of detecting that climate has changed, which, given the variability of weather and climate on different time scales is not necessarily straightforward. We combine these into the following characteristics:

1. Short run autonomous flexibility
2. Short-run non-autonomous flexibility.
3. Knowledge and capacity to undertake short-run actions.
4. Long-run autonomous flexibility.
5. Long run non-autonomous flexibility.
6. Knowledge and capacity to plan for and undertake adaptations that require changes in long-lived assets (e.g. investment, education, training, or experience with new ways of doing things).

We treat these as discrete characteristics that are either present or not. With two states (Y or N) for each of the six categories there are $2^6 = 64$ possible combinations of characteristics. We make some simplifying assumptions that reduce the number of combinations while retaining those combinations that yield quite different implications for research strategies and policy. First, we assume that adaptive

capacity (flexibility) has two states, 0 (no) or 1 (yes).[1] This assumption means, for example, that if there is short-run autonomous flexibility the system achieves its full adaptive response value of 1 without agent intervention in the short run. All other considerations are irrelevant as there is, by assumption, no more adaptive response possible.[2] We also rule out a number of outcomes by considering the role of

Table I
System response portraits defined in terms of knowledge, flexibility, and time frame

Portrait	Short-run, Auton. Flexibility	Short-run, non-auton. Flexibility	Knowledge for SR flexibility	Long-run, auton. Flexibility	Long-run, non-auton. Flexibility	Knowledgé for LR flexbility
I.1	Y	*	#	*	*	#
II.1	N	Y	Y	Y	*	#
II.2	N	Y	Y	N	*	#
III.1	N	Y	N	N	*	#
III.2	N	Y	N	Y	Y	Y
III.3	N	Y	N	N	Y	Y
IV.1	N	N	#	Y	*	*
IV.2	N	N	#	N	Y	Y
IV.3	N	N	#	N	Y	N
V.1	N	N	#	N	N	#

knowledge. We assume that the existence (or lack) of knowledge is only relevant if there exist potentially feasible approaches for increasing flexibility that are conditional on that knowledge. These assumptions are made to focus discussion on some key conceptual issues. In reality, there may be things that can be done in both the short and long run, there is a continuum of "runs" from hours to decades, and most agents find themselves faced with many different adaptation problems, and have only partial knowledge of possible response options.

Given these different categories and assumptions, only 10 of the 64 possible

[1]It is straightforward to consider adding together the various flexibilities and in some sense scoring the outcomes. With data on degree of flexibility, timing, etc., this would form the approach for numerically estimating effects but for the time being the intent is to develop conceptual portraits to help simplify the modeling problem where there is agreement on some features.

[2]Our assumption is that the shorter run and autonomous responses foreclose longer run and non-autonomous options. The other extreme assumption is that these characteristics are additive rather. A system that had each characteristic would score a 6 whereas a system that had none would score a zero. Conceptually this does not add to our discussion.

combinations remain; they are displayed in Table I. An asterisk (*) denotes a point where the 0/1 flexibility assumption eliminates a subset of possible outcomes. A # sign indicates points where the knowledge assumption eliminates a set of possible outcomes. The rows in Table I represent distinct portraits that will be the focus of the rest of the paper. We further group the 10 portraits into five broad categories for discussion purposes as labeled with Roman numerals in Table I.

In our discussion of these portraits below we focus on 4 implications: (1) Does the rate of climate change matter or is it only the magnitude of change that matters? (2) What research approaches can be useful? Can useful information on impacts be drawn from the response of systems that have developed under different climates (cross-section); is response to changing weather variability (time-series) a better guide; or, must analyses rely on structural (i.e. process-based or mechanistic) modeling of systems? (3) What strategies would be useful for augmenting or assisting system adaptation? (4) How can system characteristics lead to differential impacts of climate change across individuals and/or regions?

3.1. PORTRAIT TYPE I: AUTONOMOUS RESPONSE

If characterized by this portrait, the sector or system responds quickly without conscious human intervention, and human intervention is unable to augment the adaptation that already exists. Research on adaptation is unnecessary as there are no prospects for discovering new adaptation measures. Improved climate forecasts have no value as there are no actions one would take in response to an improved forecast. Knowing the specifics of climate effects is like knowing the date of one's inevitable death. The rate of climate change is not important because the system responds rapidly as the adaptive response is able to keep up with climate change. Climate change may have lasting effects (positive or negative) on some systems characterized by this portrait. This portrait also is one way to explain systems that are seemingly sensitive to climate but where there is little noticeable effect of differing climate conditions. Lack of substantial observed effect in operating systems is due to the fact that adaptation occurs rapidly. This can explain many estimates of the global agricultural system (e.g. Reilly 1995) or the agriculture impacts for large countries (Mendelsohn et al. 1994) that show very little net effect on global or national production even though crops are clearly sensitive to climate conditions. These estimates include many avenues for adaptation and assume that it occurs autonomously within the agricultural sector. Lack of knowledge that climate is changing is not a source of differential impacts among systems or regions because the adaptive response does not require knowledge of climate.

If a system can be characterized in this manner, then cross-section evidence on response to geographically varying climate can be useful in understanding impacts, providing that one can adequately control for other factors that vary across the

sample. As there are no dynamic responses, populations located in different climates will be in equilibrium because they adjust to new climatic conditions very quickly. Many studies have been based explicitly on this assumption: mapping exercises that identify climatic boundaries of human diseases, crops, ecosystems, or agricultural pests; observations that people live in many different climates; and more detailed statistical analyses relating cross-section outcomes such as crop production, wages, health effects of temperature, or residential property values to climate are examples of analyses that have made such assumptions. Time series data will also provide good estimates because the system responds quickly and thus response to climate is the same as the response to weather. If this portrait is an accurate characterization then detailed structural (mechanistic) studies will tend to overestimate damages unless they fully account for the autonomous adjustment.

3.2. PORTRAIT TYPE II: FAST RESPONSE WITH CONSCIOUS ACTION

Both portraits in this grouping are characterized by a system that can respond quickly but specific human actions are needed. These actions are currently known and, as long as people operating within the system are aware of the changes in climate as they occur and take action, the rate of change does not matter. Spatially detailed monitoring of climate and the communication of this information to those who must take actions to adapt, facilitates timely human action. Value to such efforts exists regardless of whether the ultimate effects of climate change are judged to be beneficial or detrimental., Without such effort, opportunities to take advantage of improved climate will be missed as well as opportunities to mitigate losses. Agents who are unaware that climate is changing will be more negatively affected by climate change so this lack of preparedness is a source of differential impacts among agents or regions (e.g. developed versus developing countries, rich versus poor). Detailed forecasts of climate for specific agents are not particularly valuable because the system can respond rapidly once the actual change is observed. Research on adaptation is not needed because people know what action to take once they observe that climate has changed.

Under this group of portraits, cross-section evidence on climate response can be misleading because it presupposes that people operating within the system will be aware of climate and take the actions needed. The adaptive policy actions the agent should take are to make sure that people operating in the system are aware that climate is changing and that they have up-to-date information on climatic trends. With this information, people operating within the system are able to successfully adapt. Contrasting evidence from time series data and process-based modeling can be useful in helping to identify the types of adjustment practices that could be useful and the extent to which people currently use them.

The two separate portraits within this group differ in that in the first there is autonomous long run flexibility that ultimately occurs if non-autonomous short-run

adaptation fails whereas in the second this autonomous long-run flexibility does not exist. In the first, even if people fail to take short-run actions, the system has resiliency, and will adjust by itself, but the slowness of the natural response will mean that there will be adjustment costs. In this case the rate of change of climate can matter. When the rate of climate change matters, adjustment costs are incurred adding to whatever negative impacts might be associated with climate change. The value of concerted action by the agent to provide information and monitoring is that all of these adjustment costs can be avoided.

In the second of these portraits, there is no natural resiliency if the agent fails to respond. Actions such as monitoring climate, organizing for adaptation, and education about the potential for climate change have added urgency, if climate continues to change because impacts resulting from the failure to adapt continues to grow as the amount of climate change increases. Differences among agents created by the failure of some to realize the need to take adaptive action will grow ever large as climate changes more. The rate of change (except as it accentuates differences among agents) does not matter because the system either adjusts quickly or does not adjust at all and hence suffers the full effects of climate change.

3.3. PORTRAIT TYPE III: PEOPLE LACK KNOWLEDGE OF WHAT TO DO

This set of three portraits have in common the idea that, in principle, there are short-run responses to climate change but people do not currently know what these are or which ones would be effective in adapting to climate change. Thus, complexities beyond those that apply to group II are added. This system characterisitic introduces the idea that climate change is something unique and different than what is observed through time as normal weather variability. People regularly deal with daily, seasonal, and interannual variability but the idea here is that those same responses are not the appropriate adaptive response to climate change. An example would be continually planting a crop in an area subject to flooding. This might be an appropriate learned response to a stable climate that had a given return period for the flooding event. While the loss is regrettable it is worth planting the crop if the risk is only, for the return period was every 10 years. But, once climate changes the owner may want to investigate other options to reduce the loss—abandon cropping, or plant shorter season crops that mature outside the flood period. This severely limits evidence drawn from time series data. Cross-section observations are also not directly useful because there is not a simple process for transferring a set of responses from one geographic location to another.

There are a number of reasons why such responses may not be easily transferred across geography. It may be the case that becoming aware of practices used elsewhere takes time and resources and that learning-by-doing is required to

adopt responses used elsewhere. Also, climatic zones and all the associated characteristics may not shift intact. Unique new patterns of climatic extremes and seasonal variability may be created unlike those that exist at other geographic locations as shifting global climate interacts with local geography. And, even if the climate conditions shift more or less intact they will be combined with a very different set of other resource and geographic conditions and hence the same responses that worked at other geographic locations may not be appropriate. This feature of a system makes it important to start research on adaptation strategies early so the research can show results in a timely fashion. Process-based modeling is required to sort out both the technological options that may work in a new environment as well as in understanding how people will respond to these new conditions.

The three portraits within this group differ to the extent that thereexist long-run options for adapting to climate change. In the first portrait within this group no long run adaptation options exist. Here there is a danger that failure to develop the necessary research on adaptation strategies will mean that the climate change damages will continue to grow over time and the gap between agents that have established the necessary research and those that have not will continue to widen. In the second, the long run adaptation response is autonomous. Thus, failure to conduct the research to find the short-run response only slows adaptation. In the third, the long run response involves conscious recognition by people that climate has changed and conscious adaptive response. The cases where response involves long run decisions (i.e. investments that are long-lived) are discussed more fully in IV below.

3.4. PORTRAIT TYPE IV: ADJUSTMENT COSTS ARE UNAVOIDABLE

In all of these portraits adjustment is costly because it involves long-lived investments (irreversibilities). As a result, prior investments become obsolete due to climate change before fully depreciated and new investments will eventually become obsolete as climate continues to change. The salient result is that the rate of climate change matters; slowing the rate of change reduces costs by extending the useful life of long-lived (irreversible) investments. Here we include the ideas of human capital (investments in training and the value of accumulated experience), social capital (community ties and relationships, shared values), and natural capital (forest stocks, soils, ecosystems) as relevant irreversible stocks that involve long-lived investments. In these portraits, cross-section evidence can be highly misleading because the fundamentally important aspect is the rate of change over time and cross-section evidence contains no information on rate of change.

Historical time series data can also be misleading if it does not contain information that allows one to estimate the effect of different rates of change on adjustment costs; i.e. if it does not include rates of climate change. Much of the

evidence from historical time series is, in fact, evidence of the response to weather variability. Effective adaptation means that the system's long-lived elements must do well on average over the types of weather conditions that will exist over their lifetime. This aspect of this series of portraits means that the system response to weather variability is not the same thing as climate change.

From an impact assessment standpoint, transient climate scenarios are needed and the impact assessment models must also capture the dynamic adjustment processes of the systems responding to climate change. Most existing studies fail to capture these costs. Comparative equilibrium costs may significantly underestimate costs they do not include adjustment costs. It is quite possible that such equilibrium comparisons would show no cost or even gains due to climate change yet the true effect could be significant losses because of adjustment costs. Regional inequities will stem from uneven projected rates of change.

The three portraits in this group differ with regard to whether the long run response is autonomous or non-autonomous and whether the adaptive response is known to people operating within the system. For the first portrait within this group the response is autonomous. As a result, there is nothing the agent can do to speed up adjustment or limit the ultimate effects of climate change. As a result, neither research into improved adaptation nor improved long-term forecasts of climate are of any use. The system will take care of itself. In the second portrait in this group, the long-run adaptation response is non-autonomous. This feature creates far more complexity for people who must respond as they must consciously detect how climate has changed before they can take appropriate action. For regions where weather is normally highly variable, it will be difficult to determine whether extreme weather events are simply part of the normal pattern of variability or whether climate has changed. Damages from infrequent extreme events such as floods provide a good example of this problem. People might wish to rebuild if a flood is the 1-in-100 year event but would not if a change in climate increased the frequency to a 1-in-10 year event. Without a fairly long time series, it would not be possible to conclude with much statistical confidence whether 2 or 3 of these events within a short time period are coincidental or evidence of a changed climate regime. In this portrait, as in those in group II, regional differences in impacts may result from differential ability to adapt. The third portrait in this group introduces the additional difficulty that the appropriate responses are not known and thus research on adaptation strategies is important.

3.5 PORTRAIT TYPE V: NO RESPONSE

The final group includes the single case where there are no adaptation options, either in the short run or long run and no ability to create them. While this portrait is in some sense the opposite of that in I (quickly and autonomously adapting as opposed to being unable to adapt at all) many of the strategies for research and the

policy implications are essentially identical to those for I. Again, cross section and time series data will provide good estimates of the impacts because time does not matter. Here physical process models provide good evidence on the impact of climate change because there is no autonomous response and no need to consider it. A useful test of whether portraits in groups I or V are an accurate description of the system is to directly compare cross-section and time series evidence. Since either data type should provide an accurate comparison of the system response if indeed the system can be characterized as such then both approaches should give the same result. If they do not, the implication is that dynamics of adjustment matter and portraits in groups II through IV likely apply.

Regarding adaptation policy implications, climate monitoring or forecasts are of no use because nothing can be done about any damages. Adaptation research is unnecessary because there is little reason to believe that adaptation strategies can be developed. In both I and V, social science research on behavioral responses is irrelevant because either the system responds by itself or there is nothing people can do to respond. Useful social science research consists largely of cross-section statistical analysis and work on determining what impacts are of interest (and how to value them) to a society that must decide whether and at what level to stabilize the atmosphere. A broader social science research agenda on whether people will respond, how they will respond, to what they will respond, or the ability of people to make decisions about climate changes that are affecting them, important in most of the other portraits, is unnecessary for these. In both portraits, the important research question is, will there be enough climate change to create significant damages? The rate of climate change is irrelevant to estimating damage levels other than providing information on when the damage will occur. In all the other portraits, there is at least a chance the rate of change will matter unless some type of adaptive strategy is undertaken.

4. Examples

We focus on examples drawn from crop agriculture and ecosystems to illustrate more concretely how the portraits of the previous section are useful in assessing impacts. Here we also integrate a discussion of scale, the agent, system definition, and interaction with other systems.

4.1 CROP AGRICULTURE

4.1.1. *Observations*

Agriculture succeeds under many different climates, ranging from tropical to cool temperate. Yet, crops are clearly quite sensitive to weather. For example, extreme heat during flowering in grain crops can cause spikelet sterility and severely reduce

yields. Droughts, floods, and storms can destroy a crop for the season. Floods and storms can also erode topsoil. Much of the research on climate change impacts on crop agriculture has concluded that net damages from climate change at large geographic scales (global and for large countries like the United States) is likely to be minimal for average global temperature increases up to about 4° C. Reviews of the relevant literature can be found in Reilly, et al. 1996; Lewandrowski and Schimmelpfennig, 1999; Reilly and Schimmelpfennig, forthcoming; and Schimmelpfennig, et al. 1996.

4.1.2. *Portraits*

Definition of the scale of the system, what is included, and the measure of performance are quite important to the conclusions one draws about the impact of climate change on agriculture. At the broadest scale (global) where the system includes the range of public and private agricultural research systems, agricultural extension, and commercial agricultural institutions and markets, and where the focus is on global food production, many observers see a system that can be characterized as I.1. The high sensitivity of agriculture to weather has led to the development of an agricultural system designed to deal with variability and changing conditions. This has led to very similar conclusions in both the first and second IPCC reports. From the Second Assessment Report, "existing studies show that on the whole global agricultural production could be maintained relative to baseline production in the face of climate change modeled by general circulation models (GCMs) at doubled equivalent-CO_2 equilibrium conditions."

A widely held view that portrait I.1 characterizes the system has led many researchers to use cross-section evidence to evaluate the impact of climate change. Belief that this portrait characterizes agriculture has also led to concern that process model approaches fail to adequately consider adaptation. Such process models can fail to consider even well-known and available adaptive strategies and they fail to consider the effects of induced innovation—i.e that differential endowments and changing prices encourage research that economizes on scarce inputs. Most process model approaches have evolved to incorporate substantial adaptation, leading to a degree of reconciliation of impacts estimates using different approaches.

Where disagreement occurs with regard to potential impacts on agriculture, the controversy can usually be traced to different definitions of the agricultural system and measures of performance. For example, some poorer countries do not have well-established research, extension, and farmer training; lack links to markets; and because the farming sector is not commercialized, new varieties adapted to changing conditions in marginal areas are not subjects for product development and marketing. Thus, the features of the commercial agricultural sector in more developed countries that make adaptation autonomous are not present in these countries, or do not operate in some of the poorer and more isolated farming

regions. Rather than global food production, some would measure performance in terms of hunger and malnutrition. Here, the autonomous nature of the market to link buyers with sellers and encourage production when prices rise does not operate successfully if the affected individuals do not have income or rights assured through other means so that their food needs can be realized as effective market demand. In these cases, portraits II.2 or III.1 may better characterize the situation. There are effective short-term solutions but the agent responsible for these systems must set them in place once the climate impact is observed. Or, as in III.1 this may involve some element of learning and adaptation of strategies effectively used in other areas. In these cases the clients for research output are national governments, food aid agencies, donor countries, and international organizations with interest in fostering improved diets for the poor.

Narrowing the client from the national government in general, to parts of it responsible for agricultural policy and research could also lead to a somewhat different characterization of the system. Here we note that the expressed confidence by many in the ability of the agricultural system to adapt must be based on responses to challenges other than climate change. The modern historical record simply does not contain actual experience in responding to global climate change. If this confidence in the system is well-placed then "autonomous" response occurs because government and commercial institutions practice adaptive management, adjust policy and research objectives to meet new conditions. The agents responsible for adapting agricultural institutions may, however, need to consider how their systems should change given the existence of climate change. Some worry, for example, that coincidental with the potential for climate change, local monitoring of climate is being degraded by budget cuts or that funding for the public research enterprise that was responsible for helping the system adapt to past challenges is shrinking.

Narrowing the scope of the system further to the individual farm where the farmer is the agent, brings in further possibilities for differential capability to adapt. Those farms that are adapting computer monitored, precision agriculture techniques and are integrated into commercial arrangements that evaluate performance and provide access to the practices and technologies that perform well are likely to be better prepared to adapt than those who lack these resources. The market system as a whole may well succeed as those that are better prepared take over the farms of those who fail.

However, those whose clients are the less well prepared see their clients' systems as portraits II.2 or III.1. This concern is similar to the "technology treadmill" phenomenon, a term coined in the agricultural economics literature of the 1950s. Those who fail to adapt just as those who fail to adopt new technology are swept out by falling profits. Whatever portrait applies, regional differences in climate impacts are likely simply because agriculture is sensitive to climate and

Table II
Speed of adoption for some major agricultural adaptation measures and associated references

Adaptation	Adjustment Time (Yrs.)	Reference
Transportation System	3-5	World Bank, 1994.
Opening New Lands	3-10	Plusquellec, 1990; Medvedev, 1987.
Variety Adoption	3-14	Dalrymple, 1986; Griliches,1957; Plucknett et al. 1987; CIMMYT, 1991.
Variety Development	8-15	Plucknett et al. 1987; Knudson, 1988.
Fertilizer Adoption	10	Pieri, 1992; Thompson & Wan, 1992.
Tillage Systems	10-22	Hill et al. 1994; Schertz, 1988; Dickey et al. 1987.
New Crop Adoption: Soybeans	15-30	FAO, Agrostat – various years.
Irrigation Equipment	20-25	Turner & Anderson, 1980.
Irrigation Infrastructure	50-75	James & Lee, 1971
Dams	75-100	Howe, 1971; James & Lee, 1971

Source: Modeled after J.M. Reilly (1995).

there is regional variation in current climate and the size and direction of change (particularly changes in precipitation patterns). At issue in the above portraits is whether comparative capacity to adapt differs between regions.

This discussion assumes that irreversibilities are not significant. If they are significant, then portraits such as IV.1 and IV.2 may be appropriate. Here there is little debate that agricultural capital infrastructure has long lifetimes. Similarly, education, training, and experience, training and crop development activities that take time. The question is, are these significant enough to matter? Dominating this question is whether the rate of climate change could be rapid enough that these irreversibilities are important. Table II provides some estimates of the lifetimes of infrastructure and speed of adoption of some agricultural technologies. These capital assets might be replaced and these time-consuming processes could be completed anywhere from about 3 times to 30 times over 100 years (an approximate

time-frame for many of the doubled-equivalent CO_2 impact studies). Will the rate of climate change suggest the need for more rapid replacement?

Where careful work to investigate this issue has occurred, the evidence is mixed that these time frames are a significant constraint for many aspects of agriculture. For example, work by Darwin et al. (1994) illustrated that much adaptation could occur on existing farmland. While opening new lands could be an additional adaptation measure, the bulk of adjustment occurred through other processes. In a study of midwestern U.S. agriculture, Yohe (1992) found little economic incentive for farmers to switch from corn to sorghum unless producers were extremely risk averse. And, Kaiser et al. (1993) also found few instances where it made economic sense for farmers to switch crops for the few U.S. sites they considered. Rather adaptation involved changes in the way existing crops were grown that need not require change in equipment and capital.

On the other hand, Adams, et al (1990) and Hurd et al. (1998) find substantial increases in are under irrigation and irrigation water demand. While water supply scenarios are not integrated in these analyses, they are concerned about whether water supplies will be adequate to meet these demands. Reductions to water supplies in some areas currently under irrigation could render these irrigation systems prematurely obsolete. Expansion of irrigation to other regions could similarly become uneconomic if water resources were to dwindle or competition from other sources increased.

Crop studies reviewed in Reilly et al. (1996) show quite severe effects for some sites under some climate change scenarios. Differential and potentially severe agricultural impacts for some sites and, by extension, local areas or regions raises broader issues of migration of people, increases in hunger and poverty, and the sustainability of the community. To address these broader issues requires reconsideration of the agent/client for regional analysis and the attendant questions of the definition of the system and measures of its performance. For highly commercialized agricultural systems, regional food supply has little to do with regional production, as the food that is produced becomes part of a national and global supply. In contrast, the community may be more interested in the economic distress of the affected farmers and related agricultural service providers, and the impacts of this distress on social services provided by the community or the impact on its overall economy. Many systems other than agriculture (water, energy, recreation, ecosystems) might be simultaneously affected by climate. As a result, the broader system might well be defined as the entire local economy, tax base, and natural resource base as in Rosenberg (1993). While this broadens the range of systems that might be affected by climate change, it also broadens the adaptation options. These options might include job training and education, efforts to attract new industry, or revising the local tax structure. A robust local economy with a very diverse economic base will have more resources at its disposal to adapt. Exploring the extent to which such a system is characterized by one or another of

the portraits in Table II thereby requires an examination of the characteristics of this broader system.

4.2 ECOSYSTEMS

4.2.1 *Observations*

In contrast to agriculture where human management of the system is heavily ingrained in the system at every level, natural ecosystems are largely considered unmanaged. Even limited management attempts, such as creating preserved areas has not always been successful because in establishing them there has been a failure to understand how the success of the preserved area is interconnected with surrounding areas that are not protected. The Florida Everglades is one example where agricultural development and water diversion in surrounding areas threatens the preserved area. In general, attempts to manage human interaction with ecosystems even on a local scale demonstrate some of the limits of our ability to understand these complex systems (Holling and Meffe, 1996; Carl and Holling, 1990). One mode of adaptation is migration. Scientists have drawn evidence from time series response to climate change drawn from pollen records in the paleo records. Table III provides some evidence on rates of migration). While there are a range of estimates, the IPCC (Kirschbaum and Fischklin,1996) concluded with high confidence that "suitable habitats for many species are likely to shift faster with climate change than the maximum natural rate at which many species can migrate and establish. Consequently, slow-growing species, such as late successional species, or those with restricted seed dispersal will be replaced by faster growing, highly adaptable or more mobile species."

Many global modeling exercises show forests migrating and responding to climate change. One of the impacts of climate change on ecosystems considered in these models is the impact on carbon storage. Many such efforts show increased carbon storage when accounting for the CO_2 fertilization effect. However, these have not included modeling of the dynamic response of forests to a climate change forcing. Those modeling exercises that have included some form of dynamic response can show significant decline in carbon storage compared with those that do not include dynamics (Cao and Woodward, 1998; Smith and Shugart, 1993). All of these global modeling exercises show significant redistribution of forests and ecosystems types. An important interpretation, particularly of the simpler redistribution model results, is that they are generally considered to be "potential" redistributions. This is because (1) human altered land use is not included so the new ecosystem type may not actually be able to establish itself, (2) barriers to redistribution (such as agricultural land) are not modeled, and (3) except for those few models that include dynamics, no assessment is made as to whether the rates of migration are possible.

A striking aspect of ecosystem research is that there is little agreement on how to measure impacts. As a result, it is unclear whether one should interpret a response of the ecosystem to climate change as a successful adaptation or as a measure of damage. Increases in carbon storage (a measure in many global studies) may occur with fast growing and invasive species. The new plant communities may lack diversity with species that are unable to compete successfully with the invading species disappearing. Candidate measures of ecosystem performance include carbon storage, avoiding loss of species, avoiding substantial redistribution of ecosystem types, preservation of ecosystems (unique, interdependent combinations of plants and animals), biodiversity, and nutrient cycling. From an anthropocentric notion of value, "products" of ecosystems include forest products, germplasm for breeding programs in agriculture and horticulture, pharmacologically active substances, many forms of recreation (hunting, fishing, hiking, camping, wildlife viewing, scenic viewing), filters for runoff from heavy rains, water storage, and existence (value people place on knowing the ecosystem exists apart from any particular use they make of it).

Further complicating measures of performance is the naturally dynamic nature of ecosystems. While there is a popular notion of "preservation" of ecosystems, modern ecology has moved away from the notion that there are equilibrium climax communities that are stable. Instead, successional ecosystem stages are more often described as "the outcome of a series of species losses and invasions, as disturbances occur and conditions change. More emphasis is now placed on the stochastic nature of vegetation change, especially in ecosystems where disturbances such as fire or intense winds are common" (Kirschbaum, 1996). Thus, even under completely "natural" conditions, the ecosystem valued by society today is likely to change.

4.2.2. *Portraits*

Scale is an issue in portraying ecosystems but the far greater issue is the performance measure of the system. Considering first carbon storage as modeled at the global level, the main conclusion is that these modeling exercises have not represented well the dynamic processes. Thus, the results can be misleading as to whether the rate of change matters and, as a result, whether irreversibilities (slowly growing trees, processes of forest establishment and soil formation, and migration) matter for the projected rates of climate change. The evidence on species migration from paleo data, as interpreted by the IPCC, suggests that these irreversibilities do matter—at least for some species. But fast growing species and invasive species could maintain net primary productivity (NPP) and carbon storage even as some species disappeared. Lack of resolution of the nature and operation of these dynamic processes means that

Table III
"Uncertainty" as reflected in divergence in estimates of the practical rate of forest migration

Migration Potential	Required Time (Yrs.)	Reference
Internationally, in response to changes in climate	10,000-20,000	Solomon & Webb III, 1985; Webb III & Bartlein, 1992.
40 - 500 meters, various species.	Annual	Davis, 1986; Torrii, 1991.
40 - 80 meters, Scots Pine in Britain	Annual	Gear & Huntley, 1991.
1 – 2 kilometers, White Spruce	Annual	Ritchie & MacDonald, 1986.

the evidence is inconclusive whether portrait I.1 or IV.1 could usefully portrays ecosystems in terms of carbon storage. While, on the one hand, the ability to maintain ecosystem value through human management is limited, on the other, forestry has developed considerable knowledge of fast growing species. Forestation activities are a commonly considered carbon mitigation policy. Thus, a strategy for maintaining carbon storage could be via interplanting of adapted, fast growing species in dying forests. If such replanting was needed every few decades as climate changed because the new species were only able to survive longer than that then portrait IV.2 might appropriately characterize the system. We would expect a stream of adjustment costs because of the need to replant different species at regular intervals dictated by the speed of climate change.

Considering the more complex notions of ecosystems as inter-related and interdependent collections of plants and animals and the measure of performance as survival of the entire collection, then the portrait we would associate with them is much different. The most certain aspect of this portrait is the lack of management options that are up to the task of assisting adaptation of ecosystems on a broad scale if they are seriously threatened by climate change. Maintaining migration corridors or more active attempts to assist in migration may be of some use, but would seem unlikely to prevent fairly substantial change (interpreted as a loss given the performance measure). Moreover, given the limited success in managing specific ecosystems, it seems a long bet to conclude that we could develop the knowledge to maintain intact ecosystems in the face of a global threat from changing climate.

The IPCC conclusion on the likely inability of species to migrate and, interpreting the maps of widespread and significant vegetation redistribution as a potential that would be achieved only with much more time to adapt, leads one to conclude that portrait V.I characterizes ecosystems. But, loosening the description of what constitutes an ecosystem, accepting change as a natural part of them, and

seeing more resilience to climate forcing in them, one could conclude that I.1 characterizes ecosystems.

If, instead, we define performance measures of ecosystems in terms of specific products of value to humans then, again, the system has different characteristics. We briefly consider forest products, species preservation and biodiversity, and recreation services. Forestry, when the focus is on production of lumber, paper, and other forest products is much like agriculture except that trees are long-lived compared with crop agriculture which is mostly annual crops. As a result, forestry portraits more likely fall in IV. Most efforts to model forest products explicitly consider dynamics of forest growth and harvest with forward-looking behavior on the part of forest managers (e.g. Sohngen, et al. 1999; Sohngen and Mendelsohn, 1998). Otherwise, many of the same considerations like the existence of the knowledge to adapt and the autonomous nature of the adaptation response, apply equally to forestry and agriculture.

For species and biodiversity, there are management options involving either *in-situ* or *ex situ* preservation. These require irreversible investments and explicit human action. *In situ* preservation, in fact, faces similar challenges as preserving ecosystems intact. Given the impracticality of listing or even knowing all species that exist, it is unlikely that *ex situ* preservation could prevent all loss. So one may wish to consider options other than preservation. For example, while specific species may be lost, crop breeding gains may be achievable through other increased scientific attention. There is some evidence that crop breeders actually make little use of the genetic material currently stored in gene banks (Mann, 1999) and biotechnology opens up the possibility of much wider use of common genetic material (Tanksley and McCouch, 1997). Thus, preservation of many close relatives of crops that can be interbred is not essential to introducing new traits. In fact, an important aspect of crop breeding is that most of the modern varieties and crops are based on a very narrow range of original genetic material., Most advances have come from the application of scientific know how and the creative use of well-known genetic material., Thus, the availability of raw genetic material is not a major constraint on breeding. Adaptation options might therefore involve making better use of existing preserved *ex situ* material and hiring more crop breeders. In situ preservation is fundamentally different in that it's never known exactly what species, never mind what genes, are being preserved. A side effect of this less focused approach to the preservation of genetic diversity is that the ecology of plant populations continues to evolve in a natural environment (Smale, 1998). Thus, from the standpoint of preserving genetic material *ex situ* for crop breeding, portraits in group IV or even II that emphasize the need to develop knowledge of adaptation options (crops with new traits) may apply. If in situ preservation is required for either broader values of biodiversity and species preservation or because of the desire to retain natural evolution of plant species then portraits I.1 or V.1 likely applies.

Recreation value of ecosystems is quite important for at least some ecosystem types. For example, one estimate is that that the recreation value of National Forests in the US is 80 percent of the total value of services provided by the forestlands with only 20 percent accounted for by timber, range, and mineral rents (U.S. Forest Service, 1995). But recreation covers a broad set of activities as noted above. Some of these depend on the existence of specific species in the wild (e.g. birdwatching, viewing autumn colors, or sighting rare plants). Much of the discussion above on ecosystem preservation is relevant and thus, portrait V.1 likely applies. For hunting and fishing the evidence is unclear as to the extent to which the value is related to being able to hunt or fish for specific species. A major data source is the periodic survey providing detail on hunting and fishing activities in the U.S. (U.S. Department of the Interior, 1997). There is some evidence that it is the experience of hunting and fishing independent of what is caught that is important. If characterized as the latter, then, even though certain specific species may dwindle, hunters and fishers can shift to other species that become more prevalent. The ability and willingness to shift to other species can be considered autonomous adaptation, requiring no specific judgement about how climate change was affecting ecosystems and species prevalence. Similarly, more work is needed to understand the extent to which the value of hiking and camping recreation experiences depend on the existence of specific ecosystems characteristics, specific climatic conditions, or other features of the landscape that may be threatened by climate change (e.g. glaciers). With recreation activities one can again expand the system to consider the full range of recreational choices the user has. If favored ecosystems migrate, the recreator can travel to visit them or adaptation could involve completely different activities.

5. Conclusion

This paper identifies factors common to a wide range of systems that might be affected by climate change. The intent in identifying these common factors is to help shed light on the adaptability of these systems. Whether systems can adapt has important implications for the extent of damages that would result from global climate change. How they adapt has important implications for whether and what type of specific adaptation strategies would be useful to encourage adaptation. These portraits also have implications for research strategies for estimating adaptation and the biases that can result if underlying assumptions are not true. We discuss 10 unique combinations of characteristics we identify as important to consider when investigating adaptation response. We refer to each as a system "portrait." We group these into 5 broad categories: I. Autonomous response, II. Fast Response with Conscious Action, III. People lack knowledge of what to do, IV. Adjustment Costs are Unavoidable, V. No response.

We conclude that many of the empirical estimates of climate change impacts use methods that implicitly assume the system they are investigating is characterized by one of these portraits rather than investigate specifically which one is actually appropriate. In fact, the two extreme portraits of I and V are often assumed. These extremes involve assuming either that the system will adapt easily, subject to the technological and economic constraints, once climate has changed or that little or no adaptation is possible. These assumptions often appear to be based on the most straightforward evidence. Specifically, many analyses involve simple, reduced form estimates of impacts using either cross-section evidence of performance of similar systems in different geographic regions or time-series response to weather and short-term variability. If systems were truly characterized as such, either cross-section or time series evidence would provide a good indication of response to climate change. Often, however, cross-section and time-series data provides much different evidence. As a result, more sophisticated research approaches are needed to estimate the impacts of climate change.

These portraits also have implications for adaptation research strategies. If adaptation is autonomous or there are no adaptation possibilities at all, then weather monitoring and evaluation of weather and climate trends, climate forecasting, or efforts to assist system adaptation are of no value. If agents must consciously recognize that climate has changed, then climate monitoring and analysis of climate trends to detect whether change has occurred is useful and a necessary component of adaptation. If there are irreversibilities then accurate weather and climate forecasting can be useful but there will still be adjustment costs stemming from the fact that investments must be made for the "average climate" that is forecast to exist over the life of the investment. And, finally where the responses one might take are not well known, research and evaluation of strategies will be a useful part of an adaptation strategy.

The broadest lessons that might be derived from our examination of adaptation is that systems can develop the institutional capability to adapt and respond autonomously. Market systems create rewards for successful adaptation and penalties for unsuccessful adaptation. An active research system, whether public or private, that is evaluating new developments in the environments in which they must perform will autonomously include changes in climate as part of the changing environment. Studying these systems and making adaptation response autonomous is the best insurance that adaptation occurs. The difficulties of projecting climate (beyond predicting weather) are substantial., Climate projection is important only to the extent there are irreversibilities (e.g. physical, human capital, social, or natural resource capital). Clearly, there are irreversibilities in almost all systems. It is not clear that investments are long-lived enough so that, given the pace of climate change, they remain long enough to become seriously maladapted.

While characteristics of systems are likely important, perhaps some of the widest disagreements in discussions of whether or not agriculture or ecosystems can

adapt stem from widely different perspectives on how the system is defined, who is the client for the research, and what are the measures of performance. Explicitly identifying the performance measure for the system is the first step in identifying adaptation potential and the adaptation options that might be considered. For agriculture, is the measure of performance national farm income, global food production, the number of hungry people, or the continued success of particular farmers? For ecosystems, should we be measuring carbon storage, germplasm, forest product production, or recreation services?

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