ASSESSING THE ROLE OF ADAPTATION IN EVALUATING VULNERABILITY TO CLIMATE CHANGE

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Abstract. Three types of adaptation can influence significantly a system's prospective longevity in the face of climate change. The ability to cope with variation in its current environment can help a system adapt to changes over the longer term. The ability to take advantage of beneficial changes that might coincide with potentially harmful ones can play an even larger role; and focusing attention on maximizing a system's sustainable lifetime can highlight the potential for extending that time horizon and increasing the likelihood that an alternative structure might be created. A specific economic approach to adaptation demonstrates that research can serve two functions in this regard. Research can play an important role in diminishing future harm suggested by standard impact analyses by focusing attention on systems where adaptation can buy the most time. It can help societies learn how to become more robust under current conditions; and it can lead them to explore mechanisms by which they can exploit potentially beneficial change. Research can also play a critical role in assessing the need for mitigating long-term change by focusing attention on systems where potential adaptation in both the short and long runs is so limited that it is almost impossible to buy any time at all. In these areas, switching to an alternative system or investing in the protection of existing ones are the last lines of defense. Real "windows" of tolerable climate change can be defined only by working in areas where these sorts of adaptive alternatives cannot be uncovered.

1. Introduction

It has become clear over the past several years that the analysis of vulnerability to global change and adaptation to its socioeconomic and/or natural effects are inexorably linked. The research community has long passed the point of considering adaptation in the abstract. Evidence of this progress is easily identified. Mendelsohn and Neumann (1999), for example, report results from a series of climate change impact analyses that span most of the potentially vulnerable market-based sectors of the United States. Each study contained there moves well beyond simply measuring vulnerability by considering market-based adaptation explicitly, and each demonstrates that the potential damage associated with climate can be reduced dramatically (and sometimes even turned into a benefit for moderate climate change) by economic actors who respond efficiently to climate change. The Ricardian (hedonic) approach adopted by Mendelsohn et al. (1994) does not incorporate specific response strategies, but it does capture the same market-based effects by reflecting how the current population of the United States has adapted to the climate that it now faces. The idea there is that people make decisions about what to do based on where they live and that those decisions are reflected in the value of land.

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Differences in the value of land can then be attributed to, among other things, differences in the local manifestation of specific climate variables under the assumption that everyone has adapted efficiently to their own particular circumstance.

Economic analyses of market-based adaptation are not the only sources of progress. Burton (1997), Smithers and Smit (1997), and Smith et al (1996) have approached the issue of human adaptation more broadly. Downing et al. (1997) and Dinar et al. (1998) have applied both narrow and broad techniques to explore adaptation to climate change in Africa and India, respectively. Various sectors, notably agriculture, water and coastal zones, have received particular attention. Agriculture was a primary focus of the “MINK” study (see Rosenberg and Crosson, 1991), for example; farmer response to a historical analog of climate change drove much of that analysis. Subsequent work by Rosenzweig and Parry (1993), Smit et al. (1996) and even Mendelsohn (1996) proceeded in the same vein with similar results – adaptation mattered a great deal when the “bottom line” was examined. Frederick (1997) and Miller et al. (1997) highlighted water issues; and Frederick et al. (1997) worked on planning issues that lay along the interface of water and coastal zones. Estimating the economic cost of sea-level rise along developed coastlines of the United States, where market-based adaptation can be expected, occupied a series of papers by Yohe et al. (1996), Yohe and Neumann (1997), and Yohe and Schlesinger (1998).

A common theme has emerged in each of the lines of research – economically based adaptation tends to lower the expected cost of climate change along smooth and anticipated trajectories. A workshop on adaptation to climate change and climate variability convened in Costa Rica by the Intergovernmental Panel on Climate Change (IPCC) in the early spring of 1998 made note of this theme. Its participants did not, however, return home reassured that climate change could be dismissed by appealing simply to the abilities of human beings respond to change. Participants emphasized repeatedly, instead, that climate change need not be smooth or anticipated, and so there is no reason to presume that adaptation will be universally effective in expanding the dimensions of tolerable change to include the full range of what might happen. Indeed, the point of this special issue is to explore the limits of tolerability by looking for response functions that could be smooth *or discontinuous*. Responding in part to the Costa Rica workshop, Chapter 18 of the Report of Working Group II of the Third Assessment Report (TAR) of the IPCC will review the state of our understanding about both. Their explicit inclusion in the TAR is clear evidence of the understanding how humans might respond to all types of change must be incorporated into the calculus of any impact assessment.

To make a contribution in this effort, though, analyses of adaptation must reveal important opportunities in areas and contexts that matter. In some cases, adaptation might prolong the lifetime of a system indefinitely. In other, more likely and more interesting circumstances, adaptation might extend a system’s productive lifetime so that substitute structures and/or systems can be envisioned and created. But research has not progressed sufficiently to support a comprehensive description of all of the significant options for adaptation that might materialize across the globe. The community has not progressed to the point where it can even offer an efficient prioritization of research initiatives designed to create such a description. Why? Because competent analysis of vulnerability *cum* adaptation is difficult to perform. It generally requires enormously detailed models (or at least the telling of very complicated stories) of not only how a system might function in its current environment, but also how it is likely to function in the future. Systems interact, as well; and so honest analysis must accommodate the second-best nature of the selection of adaptive strategies in an environment that accurately reflects the distortions caused by other responses to other issues.

Given this difficulty, it makes sense first to consider systems where the stakes are high (and if the future is discounted at all, relatively immediate in comparison with time frames that extend over centuries) *and* the potential for productive adaptation is high. Conversely, analytical effort should be expended as infrequently as possible to investigate systems where the stakes are lower and/or the potential for adaptation is relatively small. Resources that support research (denominated both in currency and hours) are, in short, scarce; and they need to be allocated efficiently. This paper speaks in part to the need to perform a triage type of sorting process by first offering a simplistic typology of three distinct forms of adaptation. It continues by suggesting general conditions under which the day of reckoning when a system will inevitably collapse might move further into the future or closer to the present. Finally, it works within those conditions to suggest the degree to which paying attention to their relatively strengths might make a difference in how vulnerability is judged in the context of foreseeable adaptive response (a weak version of the "So what?" question).

Section 2 offers an outline of the typology. Section 3 suggests how a simple, economically based modeling approach could be used to explore some of the issues surrounding two of the types identified in Section 2. A fourth section reports the results of applying the economic model loosely to the specific case of wheat-farming in Kansas before concluding remarks in Section 5 offer some summary thoughts about context - context in this special issue as well as in the growing literature on adaptation. The applied sections are decidedly economic in their perspective, but the conclusions drawn in the final section extend beyond that narrow scope.

2. Toward a Typology of Adaptation in Vulnerable Systems

Schimmelpfennig and Yohe (1996) took a first, albeit small step toward creating a practical typology of adaptive response to global change when they proposed a method for assessing relative sustainability across vulnerable systems and applied it to several agricultural activities scattered around the globe. Their measure simply tracked, over time, a sustainability index defined to be the probability that the yields of specific crops grown in specific regions would be above some critical threshold as global change distorted inter-annual patterns of temperature and precipitation. A derivative index of vulnerability was then defined simply as one minus this sustainability likelihood. They assumed, in their work, that inter-annual variability was unaffected by changes in mean temperature and precipitation suggested by the GFDL for various regions of the world. In this context, they offered evidence to suggest that northern latitude crops (spring wheat in Canada and Russia and winter wheat in Russia) and winter wheat in Australia were less vulnerable to change through the year 2050 than corn in Argentina and soybean in both Brazil and the United States. On the other extreme, corn in the United States and both rice and winter wheat in India were judged to be most vulnerable to the hypothesized climate change. Finally, they noted that switching to growing corn in the current spring wheat region of the United States identified an alternative agricultural activity for that geographic location that would be among the least vulnerable in 2050.

The point here is not to believe the specific rankings reported suggestively by Schimmelpfennig and Yohe. Their results were offered as illustrations of how one might judge the relative vulnerability to climate change of many different activities scattered around the globe. Both authors certainly recognized that the inter-annual reflections of climate changes that they imposed on the various regions were artificial. They understood, more specifically, that there was no reason to believe that current variability in temperature and precipitation would be preserved around changing means as the future unfolded. Nor did they hold that there was any real substance behind the yield thresholds with which they defined the limits of sustainability. Even in an agricultural application, these thresholds would depend on specific descriptions of how the relevant decision-makers respond to changes in their environments. In other cases, entirely different sets of decision-makers with entirely different response functions would be modeled. Schimmelpfennig and Yohe hoped that researchers would look beyond the shortcomings of their illustrative application and take their analysis for what it was - a methodological proposal designed to help them produce comparable estimates of relative vulnerability by casting the ability to cope with inter-annual variability into the context of long-term climate change. The present paper will show how their method can be used to identify and to explore, on a case by case basis, the types of adaptation might play relatively more (or less) important roles in mitigating against the increased vulnerability that might be associated with a changing climate. The hope is to be able to distinguish between cases in which the ability to adapt to change would matter from cases in which it would not.

This paper builds, more specifically, on their index-number approach to contemplate how the threshold of sustainability might be determined in the context of potential adaptation to its effects of climate change. In so doing, it will suggest that at least three different types of adaptation need to be considered before a decision simply to protect a system from change can be made. It will also confirm the obvious expectation that the relative importance of each type of adaptation

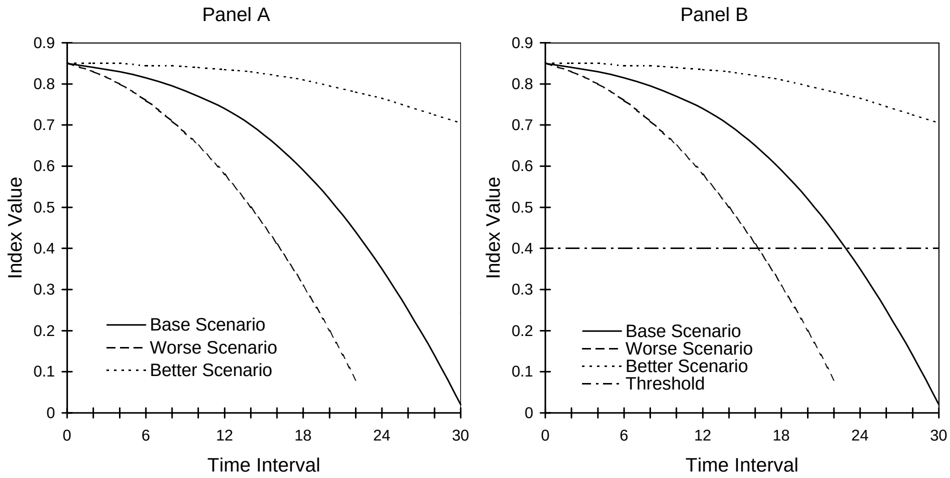

Figure 1. Panel A. Representative trajectories of a sustainability index tracked over time in the context of climate change.

Panel B. Representative trajectories of a sustainability index tracked over time in the context of climate change and cast against a threshold limit for sustainability

can be expected to change from situation to situation. Panel A of Figure 1, for example, portrays a simple representation of the sort of trajectories that might emerge from the application of the Schimmelpfennig and Yohe method to any social, economic, political or natural system as it faces the increased stress of a changing environment. Units along the time axis reflect intervals of unspecified length to highlight that the method can accommodate any pace of change. The "base" scenario has been drawn arbitrarily to provide a point of reference. It suggests that climate change would become an acute problem for this system around the 16th time interval when its sustainability index value begins to fall precipitously (e.g., when the manifestations of the then current climate begin to fall outside the bounds of tolerability with alarmingly high frequency). Two other scenarios are also depicted. One is "worse", turning down earlier and more quickly along the same underlying climate change scenario. The other is "better"; it hardly changes over time, indicating the possibility that climate change could have little effect on the system's viability even over the very long term.

Panel B of Figure 1 builds on Panel A to suggest that the evaluation of a system's vulnerability to climate change can quickly turn from questions of whether it faces collapse to questions of when that collapse might be expected to occur. The structure portrayed in Panel A is completed in Panel B by assuming that there is a minimum level of sustainability that is consistent with the system's ultimate viability. In an agricultural application, this limit could be taken to be a minimum likelihood that a farm's yield per acre in any given year would exceed a threshold that defines economic viability. In a different application, the assumption might reflect a system's passing beyond the population threshold of its biological sustainability. In fact, the exact definition of this threshold could depend upon a variety of things that would be different for different types of systems. In an economic context, risk aversion would play a role. In a managed ecosystem, the ability of humans to protect the system from the impact of change would be important. In an unmanaged ecosystem, the ability of the system, itself, to migrate might be critical. These and other issues are complicated and would need thorough examination. Evaluating their potential significance and exploring the timing of their criticality would certainly be first steps in defining the limits of tolerable change.

The first two trajectories drawn in Panel B pass below the arbitrary sustainability threshold roughly 18 and 23 time intervals into the future. These are the "worse" and "base" case scenarios, respectively. The "better" scenario, by way of contrast, reflects the possibility that sustainability along a future change scenario might never turn down. In that case, a system could be deemed sustainable well into the indefinite future even with climate change. If that were not the case, though, more time before collapse would always preferred to less time so that people would have more time to decide what to do. The three scenarios portrayed in Panel B therefore highlight a critical question driven by the timing issue: under what circumstances might adaptive potential make a better trajectory (i.e., a flatter and higher trajectory) more likely; and, conversely, under what circumstances might more limited adaptive potential lead to a worsening outlook?

Table I has been constructed to shed some light on a few of the answers to these questions. The first two parts, in particular, differentiate between near- and longer-term adaptation. Near-term adaptation emphasizes a system's ability to respond effectively to the inter-periodic variability that defines its current environment. Agents in a system who are particularly adept at dealing with even large short-term variability simply sustain systems that are stronger and more robust over both the short and longer terms. Their current strength can steel them against the vagaries of a future change that makes the bad states of nature in their current world more likely. They may have more access to financial capital with which to underwrite adaptive strategies. They may have already adopted technologies and decision rules that allow them to guard against suffering significant damage when bad things happen. They will certainly have developed means with which to monitor change. It really doesn't matter why they are more robust. All that counts is that the ability to be extra-marginal in the current environment (drawn from any source) can frequently buy some time in the sense of slowing an inevitable downturn in sustainability associated with any deleterious global change trajectory. Indeed, an ability to cope with short-term variability could delay a downturn in sustainability almost indefinitely.

If current strength can make it more likely that a better scenario will emerge, however, then it is equally true that current weakness could portend a worsening future even in comparison to a baseline portrait of the future. It is almost a tautology to assert that marginal systems facing wide inter-periodic variability in their

TABLE I
A typology of adaptation to climate change

Adaptation type	Moving from base to better	Moving from base to worse
1. Respond in the short term to inter-periodic variation	(a) Smaller sensitivity of performance across possible range (b) Smaller range of variability	(a) Larger sensitivity of performance across possible range (b) Larger range of variability
2. Respond to long-term and persistent change	(a) Single variable change that is beneficial (b) Multiple variables changing: some are beneficial and sufficient flexibility to exploit benefits	(a) Single variable change that is harmful (b) Multiple variables changing: none beneficial or some beneficial but less significant or some beneficial but little ability to exploit the benefits
3. Switch activities	(a) Anticipate change correctly and (b) Prepare effectively to exploit benefits	(a) Anticipate change incorrectly and/or (b) Prepare ineffectively to exploit benefits

environments with limited abilities to read that variation and/or act appropriately to minimize damage are among the most susceptible to any amplified deterioration caused by the forces of global change.

The second section of Table I focuses attention on productive adaptation that differs from the first in part because it demands analyses that look further into the future. Its potential is clear whenever it is recognized that global change will, in all likelihood, manifest itself in many dimensions. Some of its effects might be bad and impose increased stress on a system, but some of its other effects might actually be beneficial and offer ways of alleviating that stress. If the beneficial changes are or could be important in sustaining a system and if there were ways of exploiting the opportunities that they might bring, then surely adaptation would offer the chance to move to a “better” scenario. If that were the case, then even an inevitable collapse in the face of climate change could be delayed. If all of the changes were bad or if the potential benefits did not and could not play an important role sustaining a system, though, then the likelihood of the “worse” scenario and its associated precipitous decline should rise.

The third part of Table I finally recognizes the frequently overlooked potential that adaptation in the face of the inevitable collapse of one system could involve its

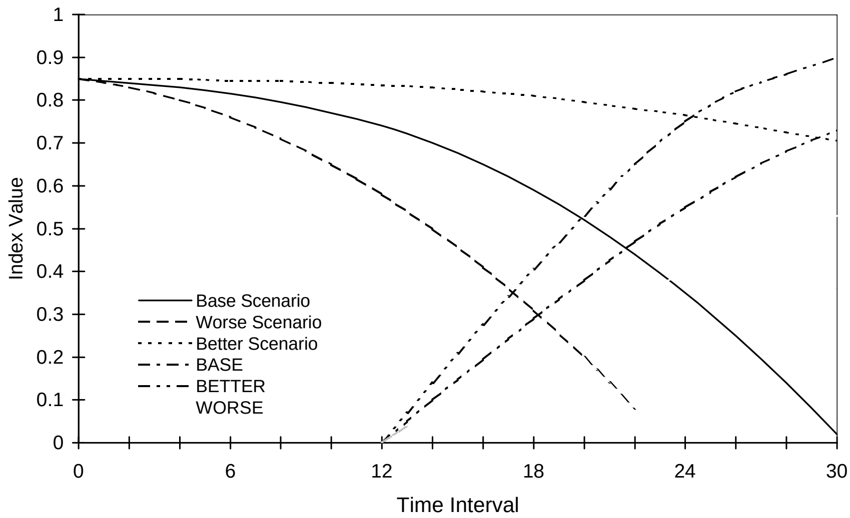

Figure 2. Representative trajectories of a sustainability index tracked over time in the context of climate change and cast against the trajectories of an alternative activity that will become sustainable as the climate changes.

replacement with a viable alternative (even if it cannot now be sustained). Suppose, for the sake of argument, that a community's well-being depended fundamentally on an existing economic or natural system (say, system A) that would be vulnerable to climate change. Might it not be possible to design an alternative support system (system B) that would be more viable in the anticipated future climate? Community welfare would surely depend on individuals' confidence that system B could sustain their community *and* their understanding that system A would not be sustainable over the foreseeable future. As a result, increasing the time available before any transition were required could be valuable, but only if the extra time were required to allow system B to mature sufficiently as the climate changes *and* if the declining system had not yet collapsed. Switching from system A in the last stages of its rapid decline to system B while it were still in the initial tentative and unsure stages of development would marry the worst aspects of both, especially if the transition thereby spanned a time when neither were fundamentally sustainable. Figure 2 depicts all of these possibilities by superimposing three possible scenarios for the development of switching alternative onto three declining scenarios for the first system. As drawn, the alternative (system B) begins to emerge as a potential option no sooner than the 14th time interval, and it is not likely to be sustainable for some time after that.

Correct and efficient anticipation of the workings of the alternative could, however, accelerate the process of building its sustainability and supporting its more rapid adoption. Suppose that a switch from reliance on system A to alternative system B were modeled to occur only when the system B became more sustainable than the threatened system and sustainable in its own right. As drawn in Figure 2, the system B might be able to replace system A even along the worse scenario before things get too bad (i.e., for example, before the index for the first system falls below the previously chosen threshold of 0.4). System B could even replace A along the base scenario well before A began its precipitous decline. Anticipated poorly, however, the role of the system B as a replacement would materialize uncomfortably late in the day along the worse scenario. It could appear, in fact, well into the period of significant decline even along the better scenario and below the specified (but, again, arbitrary at this point) threshold of collapse in the base case.

Three types of adaptation have been described in Table I and illustrated schematically in Figures 1 and 2:

1. adaptation on a routine basis to inter-period variability in the current environment, especially in response to observable changes in variables likely to be influenced by global change;
2. adaptation over the longer term to global change, itself, especially taking advantage of any components global change that prove to be beneficial; and
3. switching to new systems designed explicitly to be more sustainable as global change progresses.

There are surely other types of adaptation that do not neatly fit into one of these three categories. Most notable, perhaps, are system specific and potentially expensive interventions designed to protect an existing system completely from the effects of global change (avoiding the symptoms of the change by blocking them by e.g., building seawalls to protect property against sea-level rise). These sorts of interventions are, however, typically considered only after an existing system has actually been deemed to be vulnerable, but such a determination can be accomplished only in full recognition of the range of more subtle adaptations reflected in Table I. Large intervention projects are, therefore, left for more system specific analyses. In addition, the remaining discussion will drop the third type of adaptation noted in Table I from consideration. Switching has been considered elsewhere (witness the spring wheat to corn result in Schimmelpfennig and Yohe, 1996 and the varied farm practices highlighted in Rosenberg and Crosson, 1991 as two examples); and it, too, generally comes into play after extreme vulnerabilities are recognized for a specific system. The first two types of adaptation identified above can, by way of contrast, play a critical role in uncovering truly extreme vulnerabilities, and so the next two sections will focus attention only on them. Section 3 will suggest how their potential interactions might be examined using simple economic theory, and Section 4 will use the resulting model to explore their relative magnitudes in a simple example.

3. Toward a General Method of Modeling Adaptation in a Vulnerable System over the Short and Long Runs - an Economic Perspective

Simple microeconomic theory can be used to provide a precise description of the sustainability of an economic activity directed by an economic agent who strives to maximize profit in the face of inter-periodic variability in, say, the efficacy of production. Consider, for example, a farmer who operates as a price taker in an uncertain environment where the yield from his fields for any one period is drawn from a gamma distribution (that itself depends upon, among other things, precipitation and temperature). The farmer must cover his fixed costs every year (unavoidable costs derived from the very act of keeping a farm running in any given year), but he could avoid paying variable cost (costs that depend upon the amount of land actually planted and maintained through harvest time) by not planting anything. If he knew exactly what yield would be before he had to decide when and what to plant, then he

- would choose to plant nothing (but still pay the fixed cost of sustaining a farm for the season) if yield were so low that revenue would not cover the variable cost of bringing a crop to harvest (the “shut-down” yield); but
- would choose to stop farming permanently if the expected value of revenue net of variable and fixed cost across the full range of possible yields were not positive.

These are the familiar decision rules attributed to price takers in a certain world by the foundations of microeconomic theory.

In an uncertain world, the very same farmer faced with making his planting decisions knowing only the expected yield for that period (perhaps because he knew a little about anticipated temperature and precipitation, but not enough to estimate yield exactly) would do something different. He might then consider a decision rule that would see him plant nothing if the expected yield for that season were below some threshold “yield limit”. This yield limit threshold would lie above the “shut-down” yield noted above and would thereby function as a hedge against states of nature in which the revenues to be generated by taking a crop to market would not even cover variable costs. A “risk premium” would be added to the difference between the two yields if the farmer were at all averse to risk. Even without risk aversion, though, uncertainty about the price would increase the hedge, as would some negative correlation between price and yield. Even absent all of that (and more, no doubt) complication, the farmer would still give up the farm if the expected value of revenue net of variable cost (incurred when crops were planted) and fixed cost were not positive.

It is not difficult, in this simple environment, to envision constructing a contour that reflects all of the combinations of yield limit (y_l) and mean yield that would support some positive level of expected profit. Each contour would, of course, be defined for some specified fixed cost and a well-defined correlation between

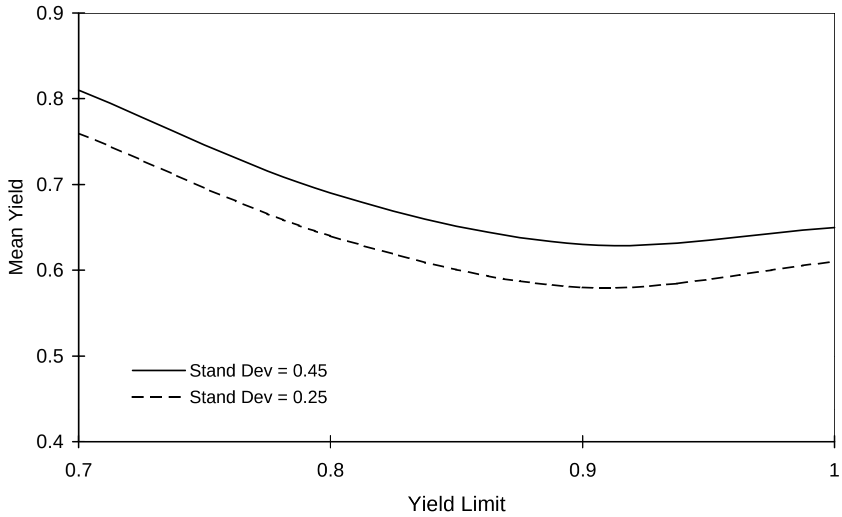

Figure 3. Representative probability/sustainability contours indicating combinations of mean yield and yield limit that support the same level of profitability cum sustainability

variable cost and the area planted. Figure 3 shows a few for the usual zero (economic) profit decision-rule and a particular manifestation of the climate. They all converge to the "shut-down" yield (y_o) as the mean yield climbs because the necessary hedge shrinks. They all display a minimum, as well - the lowest mean yield consistent with any possibility of meeting the profit constraint. Both the shape and the locations of these contours are important, but their general content is easily stated. A farmer operating in an environment described by a higher contour is more vulnerable because he needs higher mean yields and/or the potential of deciding on the basis of a higher yield limit to stay in business. Higher fixed costs mean higher contours, all other things being equal. So do higher variances in yield around any mean, lower prices for product, uncertain prices for product, prices correlated negatively with yields, and so on.

The comparison drawn between the two contours depicted in Figure 3 is described in terms of differences in variance for the same fixed cost, but they could serve equally well to differentiate condition along this long list of critical factors. It is important to note that some, but not *all*, of the factors can be controlled by the farmer. Nonetheless, the higher the contour, the larger the vulnerability in the short run and, it will turn out as suggested in Table I, the smaller the effective potential for making productive adjustments over the longer term to delay the inevitable collapse of the farm.

Similar geometry can be used to track the effect of progressive global change over time. Suppose that the farmer just described were faced not only with uncertainty about current yields given the current climate, but also with uncertainty about future yields and how their distributions might change over time. It would then be possible, in general, to track the mean yield that would be produced by the farmer's using various yield limits in the plant-or-don't-plant decision rule along any global change trajectory defined by assumed intertemporal changes in the distributions of temperature and precipitation. Trajectories of the sort illustrated in Figure 1 would result (with mean yield plotted over time rather than a sustainability index). Higher trajectories would be better news, and several of the points noted in the second section of Table I suggest when the news might or might not be better.

Assume, both for the sake of argument and for the sake of supporting an interesting story, that increased temperatures would be harmful (would reduce mean yields) and that increased precipitation could be beneficial (would increase mean yields, at least up to a point). In that case, then a global change scenario that included both would test the ability of an existing system to mitigate against the damage of warmer temperatures by exploiting the benefits of the enlarged rainfall. Intertemporal mean yield trajectories would shift up, to some degree, and the inevitable move toward the collapse of the farm might be slowed. Conversely, higher yield limits imposed by the farmer would shift the time trajectories down (adding more to the "shut-down" tail of the farm experience), as would larger variances in either temperature or precipitation.

Since Figure 2 has instructed that timing important, it turns out to be informative to use sets of these intertemporal trajectories to craft "isointerval" contours - combinations of yield limits and mean yields that would occur at the same time in the future for a given global change scenario. The two panels of Figure 4 displays a few of them. They all slope downward because higher yield limits produce lower mean yield trajectories and so mean yields are lower after any fixed interval of time. They are all concave because the lower trajectories of the higher yield limits also fall more quickly over time. Since a well-developed ability to substitute increased precipitation to mitigate against the damage caused by higher temperatures pushes mean yield trajectories higher, it also pushes any isointerval contour higher. So does any increase in the relative importance of precipitation over temperature in determining yield. The contours displayed in Panel A of Figure 4 differentiate across time - longer intervals associated with lower contours. Panel B, by way of contrast, illustrates how higher contours for the same interval are associated with more substitution potential and/or a larger role for precipitation in determining yield.

The purpose of drawing these two types of contours in a space defined by mean yields and yield limits is practical. Taken together, collections of both types allow the combined short and long term adaptation questions to be cast as one of constrained optimization. The idea would be to maximize the length of time that a vulnerable (agricultural) system can be sustained (i.e., moving the system down to its lowest isointerval-interval contour) subject to the (profitability) constraint that defines sustainability. Section 4 portrays how the structure might work and explores a specific application.

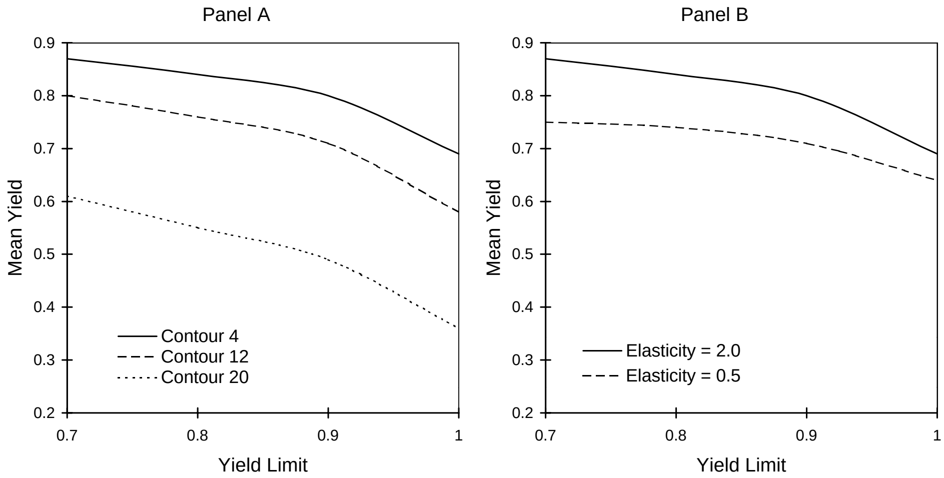

Figure 4. Panel A. Representative contours indicating combinations of yield limit and mean yield consistent with specific intervals of climate change for an elasticity of 2.0 – a value that reflects relatively large abilities to mitigate against the damage of (e.g.) increased temperature by exploiting the benefits of increased precipitation.
Panel B. Representative isointerval contours indicate combinations of yield limit and mean yield consistent with 4 intervals of climate change for two cases. One (with an elasticity of 2.0) reflects a relatively large ability to mitigate the damage of (e.g.) increased temperature by exploiting the benefits of increased precipitation; the other (with an elasticity of 0.5) reflects a more limited ability to accomplish the requisite "substitution" of precipitation for temperature.

4. A Specific Illustration - Can Adaptation in the Short and Long Runs Both Play a Role in Determining the Longevity of a Vulnerable System?

To begin to describe more fully a decision environment within which the constrained maximization just framed might be applied, suppose that the yield per hectare of planted land in any period t (y_t) were, for the farmer highlighted in the second section, given by

$$y_t = \alpha_t Y_t,$$

where Y represents a normalizing calibration value and α_t characterizes the interperiodic uncertainty in yield with which he must deal. Let α_t have a gamma density function each period, and expect that both the mean and standard deviation of that function will change with climate change. Assume further that the factors that support fixed and variable cost for the farmer display constant returns to scale in their relationship with yield (i.e., assume that creating an exact duplicate of the farm in question would double output). In that case, marginal and variable cost for any y_t can vary inversely with the square of α_t (actually inversely with α_t raised to a power that is itself inversely proportional to the share of yield devoted to paying

TABLE II

Responses of mean yields to changes in the interannual distributions of temperature and precipitation (kg wheat per hectare) - Topeka, Kansas

Responses to temperature change	
Base yield	4208
Max/min temperature increased by 2°C	3398
Same temperature change with doubled variance	2470
Same temperature change with 50% variance	3808
Responses to changes in precipitation	
Base yield	4208
Mean precipitation increased by 20%	4761
Same mean increase with doubled variance	4337
Mean precipitation decreased by 20%	2982
Same mean decrease with 50% variance	2940

Source: Tables 2 and 3 of Mearns et al. (1996).

fixed cost when economic profit is zero). This is exactly the situation that produced the "Profitability/Sustainability Constraint" contours drawn in Figure 3 with:

- fixed costs set equal, on average, to 12% of total cost when economic profit was zero;
- Y normalized to unity for simplicity;
- the standard deviation of α_t set equal to either 0.25 or 0.45; and
- the price of output set above the minimum of average variable cost whenever α_t = 1.

Note that the contours drawn in Figure 3 do not reflect convergence to a perfect foresight "shut-down" yield. Leftward extension of the horizontal axis would, however, allow them to highlight this limit at approximately 0.5.

Having constructed a reasonable static environment that can accommodate simply some decision-making under uncertainty, it remains only to describe how global change might distort its parametric description. Guidance in this task was taken from some recent work designed to support the creation of response surfaces along which the impacts of global change might be judged. Table II records, more specifically, estimates on the sensitivity of the yield per hectare to changes in the mean and variance of both temperature and precipitation derived from the CERES-Wheat Model for conditions attributed to Topeka, Kansas in the United States by Mearns et al. (1996). Indeed, Table II summarizes the content of their Tables 2 and 3.

The “Isointerval-interval” contours drawn in Figure 4, in fact, display the results of fitting (loosely) the sensitivities reflected in Table II within what could be termed constant “elasticity of substitution inter-periodic yield functions” in precipitation and temperature. Each

– reflected the Mearns et al. (1996) sensitivity of mean yields to changes in precipitation and temperature (taken separately);
– accommodated changes in the variance of yields associated with changes in precipitation and temperature; and
– accommodated different, but constant, elasticities of substitution between precipitation and temperature.

Each elasticity of substitution required a different specification of the yield function, to be sure, but each different specification simply reflected a different ability to substitute the beneficial effects of increase precipitation (through a 20%) for the damaging effects of higher temperatures. Higher elasticities of substitution indicated improved ability to substitute precipitation “for” temperature (i.e., to compensate for damage caused by higher temperature) if and when it becomes available.

The fitting process that supported Figure 4 was, however, more qualitative than scientific. It sought to parameterize yield functions so that would mimic yield behavior for the specific changes in the mean and variance of precipitation or temperature reported by Mearns et al. (1996). While it was not possible to fit the functions along transient trajectories of change, the parameterizations did reflect reported changes in variance reasonably well; and so it is not too much of a stretch to suggest that they do not behave too badly between reported “checkpoints” of climate change.

Figure 4 also relied on the specification of global change scenarios. Transient trajectories of regional precipitation and temperature patterns are suspect, of course; but having demonstrated that even sparsely described “response surfaces” can be accommodated, there was no need to rely on any reported trajectory for present purposes. The point was to illustrate the potential significance of characteristics like the ability to benefit from higher precipitation even in the face of damaging changes in temperature and to display its role in increasing the sustainability of a vulnerable system. It made more sense, therefore, to look at three simple scenarios: (a) mean temperature climbs by 2°C over 30 time intervals; (b) mean annual precipitation climbs by 20% over 30 time intervals; and (c) a combination of both of the above.

Panels A and B of Figure 5 reflect the resulting transient trajectories of mean yield for an assumed yield limit of 0.8 and two elasticities of substitution - one relatively low (0.50) and one relatively high (2.00). Notice that higher temperatures alone are harmful and that higher rainfall alone is beneficial in either case (at least through a 20% increase in precipitation where its beneficial effects are maximized). Notice, as well, that allowing both to occur simultaneously produces intermediate

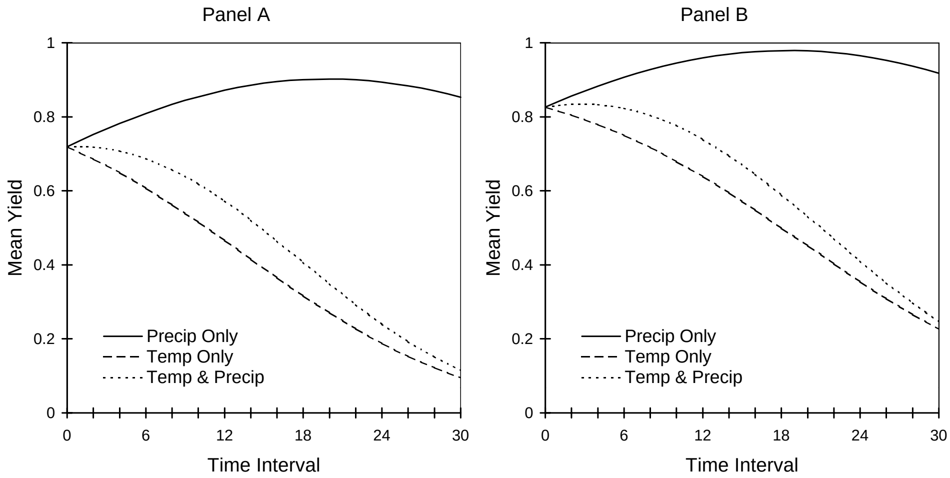

Figure 5. Panel A. Representative mean yield trajectories for wheat in Topeka. Each assumes a *limited* ability to mitigate the damage caused by higher temperature (taken to be 2 degrees through the 20th interval and continuing linearly thereafter) by "substituting" increased precipitation (taken to include a 20% increase through the 20th interval followed by symmetric decline)
Panel B. Representative mean yield trajectories for wheat in Topeka. Each assumes a *significant* ability to mitigate the damage caused by higher temperature (taken to be 2 degrees through the 20th interval and continuing linearly thereafter) by "substituting" increased precipitation (taken to include a 20% increase through the 20th interval followed by symmetric decline)

trajectories that lie closer to the best precipitation-change-only trajectory for the higher elasticity of substitution. This is a general and intuitively appealing result. The link between Figures 4 and 5 can be seen most clearly by noting, for example, that the ordered pairs (4 , 0.71) and (4 , 0.83) which lie on the transient trajectories of Figure 5 for the low and high elasticity cases, respectively, correspond directly with the order pairs (0.8 , 0.71) and (0.8 , 0.83) which lie on the 4-unit isointerval contours drawn in Panel B of Figure 4.

Turning, finally, to putting the two components together, consult Panels A and B of Figure 6. Both show results for the third choice listed above - the mean temperature increasing 2 degrees over 30 time intervals while precipitation climbs by 20%. Panel A shows that the lowest "isointerval-interval" contours lie tangent to the two "Profitability/Sustainability" constraints at 9 and 12 intervals for the low elasticity case and at 15 and 17 for the high elasticity case. Higher intervals are thus shown for lower variation in inter-periodic variability in yield for either elasticity, so better inter-periodic conditions can lead to increased longevity for a vulnerable system. Holding inter-periodic conditions constant, by way of contrast, shows an even more dramatic effect - with increased ability to use precipitation to ameliorate the effect of higher temperature also adding longevity. Indeed, as seen in Figure 7, going from bad news in both the short and long runs (high inter-periodic variability and little substitution potential) to good news in both categories (low inter-periodic

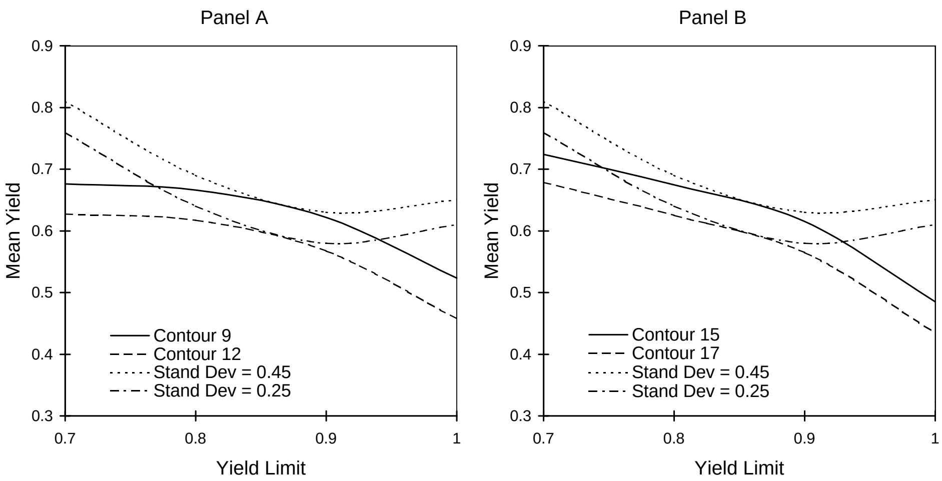

Figure 6. Panel A. Representative constrained maximization of sustainability assuming a *limited* ability to mitigate the damage caused by higher temperature (taken to be 2 degrees through the 20th interval and continuing linearly thereafter) by "substituting" increased precipitation (taken to include a 20% increase through the 20th interval followed by symmetric decline)
Panel B. Representative constrained maximization of sustainability assuming a *significant ability* to mitigate the damage caused by higher temperature (taken to be 2 degrees through the 20th interval and continuing linearly thereafter) by "substituting" increased precipitation (taken to include a 20% increase through the 20th interval followed by symmetric decline)

variability and high substitution potential) can nearly double the longevity of the modeled activity from 9 intervals to 17.

5. Some Concluding Remarks in Context

Concluding remarks on the narrow focus of the illustrative analysis must begin with the usual caveats about believing the numerical results. These caveats apply with a vengeance, here, because the models that underlay the illustration are so simplistic and the summary representations of climate change are so arbitrary. Still, even exercising simple models within minimally complex climate change scenarios suggests that the theoretical construction is reasonably robust - capable of accommodating many representations of how adaptive decisions might be made and many representations of climate change. All that is required, really, is that the impact of climate change be displayed in terms of the sensitivities of a vector of critical environmental parameters to that change. Indeed, recent work that pursues response surfaces for a wide variety of economic, social and political systems (some of which is described elsewhere in this special issue) should easily feed directly into the methods proposed here.

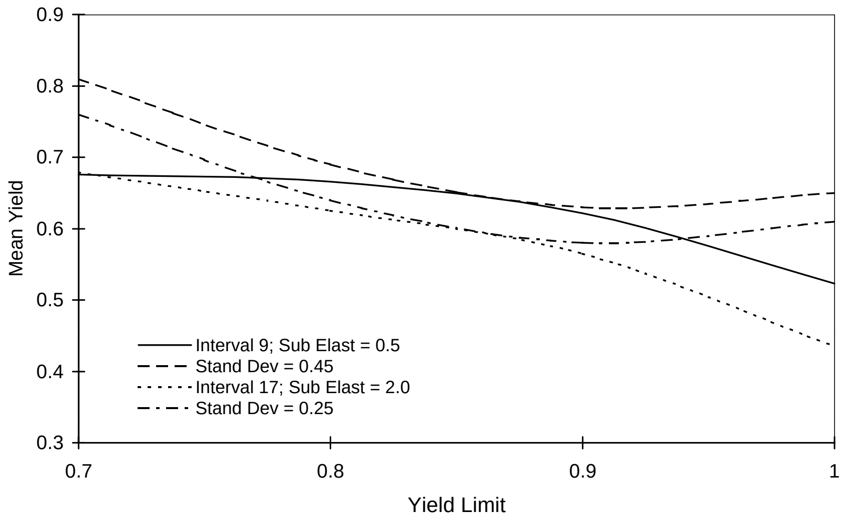

Figure 7. Representative constrained maximization of sustainability assuming different abilities to mitigate the damage caused by higher temperature (taken to be 2 degrees through the 20th interval and continuing linearly thereafter) by "substituting" increased precipitation (taken to include a 20% increase through the 20th interval followed by symmetric decline) and different current interannual variability

Concluding remarks that reflect context must, meanwhile, return to the issue of improving the ability of the research community to select arenas in which careful analysis of the role of adaptation in evaluating vulnerability to climate change might pay the largest dividends. In that regard, the qualitative results reported from the illustrative models underscore the significance of Table I. At least three types of adaptation can, indeed, influence significantly a system's prospective longevity in the face of climate change. The ability to cope with variation in its current environment can help a system adapt to changes over the longer term. The ability to take advantage of beneficial changes that might coincide with potentially harmful ones can play an even larger role. Focusing attention on maximizing a system's sustainable lifetime highlights the potential for extending that time horizon and increasing the likelihood that an alternative structure might be created. Timing is the key, and more time is better than less time.

Research can serve two functions in this regard. It can, on the one hand, play an important role in diminishing future harm suggested by standard impact analyses by focusing attention on systems where adaptation can buy the most time. It can help societies learn how to become more robust under current conditions; and it can lead them to explore mechanisms by which they can exploit potentially beneficial change. Research can, on the other, play an equally critical role in assessing the need for mitigating long-term change by focusing attention on systems where potential adaptation in both the short and long runs is so limited that it is almost impossible to buy any time at all. In these areas, of course, switching activities and/or protection projects form the last line of defense. Real "windows" of tolerable climate change can be defined only by working in areas where these sorts of adaptive alternatives cannot be uncovered.

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