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Global Environmental Change and Agriculture

Assessing the Impacts

Edited by

George Frisvold
Department of Agricultural and Resource Economics,
University of Arizona

Betsey Kuhn
Economic Research Service,
US Department of Agriculture

NEW HORIZONS IN ENVIRONMENTAL ECONOMICS

Edward Elgar
Cheltenham, UK • Northampton, MA, USA

Published by
Edward Elgar Publishing Limited
Glensanda House
Montpellier Parade
Cheltenham
Glos GL50 1UA
UK

Edward Elgar Publishing, Inc.
6 Market Street
Northampton
Massachusetts 01060
USA

A catalogue record for this book
is available from the British Library

Library of Congress Cataloguing in Publication Data

Global environmental change and agriculture: assessing the impacts /
edited by George Frisvold, Betsey Kuhn.
(New horizons in environmental economics)
Includes bibliographical references.
1. Global environmental change. 2. Climatic changes—
Environmental aspects. 3. Agriculture—Environmental aspects.
4. Environmental auditing. I. Frisvold, George B. II. Kuhn,
Betsey. III. Series.
GE149.G55 1998
338.1'4—dc21 97–32759
CIP

ISBN 1 85898 631 1

Printed and bound in Great Britain by
Biddles Ltd, Guildford and King's Lynn

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6 Vulnerability of Crops to Climate Change: A Practical Method of Indexing

David Schimmelpfennig and Gary Yohe

1 INTRODUCTION

Consideration of how to respond to climate change frequently turns upon the evaluation of the undesirable consequences of some possible effect of that change. For coastal property, for example, sea level rise might inundate homes or cause salt water to intrude on sources of fresh water. In the agricultural sectors, hotter climates might cause crop yields to fall, with or without prudent adaptation. If we think of the consequences of climate change as the result of crossing a physically determined threshold, then it can be instructive to consider the probability of reaching that threshold under various states of the world. Initially ignoring the potential for adaptation can allow the research to focus on crops and growing regions where adaptation might be the most helpful.

We begin with the notion that the probability of crossing a threshold can be a workable metric of vulnerability. The idea of action thresholds was proposed by participants in a landmark international conference held in Villach, Austria (SCOPE, 1985) and it has been emphasized again in the highly visible Intergovernmental Panel on Climate Change (IPCC) assessment reports (IPCC, 1996). This chapter will add to that discussion and to our knowledge about thresholds by developing a uniformly applicable index to characterize probabilistically, the crossing of one or more thresholds. The vulnerability index accounts for uncertainty in our understanding of how the climate might be changing *and* uncertainty in our understanding of the consequences of climate change. A complementary index of sustainability is simply one minus the vulnerability index.

The choice of a threshold level is crucial for policy applicability. In the past, attempts to identify and avoid thresholds have led to the development of several rules of thumb that have been useful in policy settings. Roumasset (1976) discusses three safety-first rules of thumb. The 'safety principle' minimizes the probability of crossing the threshold, and the 'strict safety-first principle' maximizes an objective, like farm profits, subject to the constraint that the threshold should not be crossed. The third general category of threshold avoidance strategies is the 'safety-fixed principle' that attempts to hold the probability of crossing the threshold constant while maximizing the lowest level that farm profits can fall to.

In choosing the level of the threshold in the chapter we considered that, if the threshold were too low, it would be reached under circumstances that might be considered innocuous. If the threshold is too high it will be reached after the majority of the damage has been done. The threshold that we consider is a 10 percent reduction below trend in the yields of six major cereal crops. This is probably too high in some circumstances and too low in others. As will be shown, U.S. corn historically shows more natural variation to changes in weather patterns than some of the other crops considered and, for that reason, it might be appropriate to consider a higher threshold for U.S. corn.

In the final analysis, though, it is likely to be the individual farm affected by climate change that matters. For socio-economic reasons, important thresholds might be different for different farms in different regions even growing the same crop. Adaptation to climate change would proceed at different rates at different farms, so the effects of climate change should be offset at different rates (Morrisette and Rosenberg, 1992). Systems, in general, can and will adapt to change; and that adaptation can be encouraged and supported by policy. That is the point of recent studies conducted by the IPCC (1990, 1992, 1996), the U.S. National Academy of Science (1992), the Office of Technology Assessment (1993), Lewandrowski and Brazee (1993) and Schimmelpfennig (1996).

Adaptation will take place, but it is a mistake to think of adaptation as occurring simultaneously with perceived changes in the environment. Some of the lags in the adoption of agricultural adaptation measures are quite long even on the time scale of global warming, as the summary of related research in Table 6.1 shows. These time lags reflect the fact that many adaptation measures require investments in capital that are expensive and lock a farmer into the use of the new technology, at least until the investment pays for itself. In fact, the new technology is probably replacing another technology that is itself on an amortization schedule, further slowing down the adoption of new technologies as the farmer waits for the old technology to wear out. Several other factors contribute to time lags in adaptation. Time is required to carry out test plot experiments in the development of new seed varieties. Time is required to educate farmers about new practices. More commonly in developing countries, the lack of adequate infrastructure, an extension service and even cleared land can slow adoption of new agricultural technologies. Our vulnerability index could be used to help farmers evaluate the need for new technologies by indicating the vulnerability of their current crop absent adaptation. It would be fairly straightforward, with the help of extension agents with the appropriate computer software, for a farmer to develop the limited data required to generate the index for an individual farm. The index is not a policy tool in the

Table 6.1 Speed of ad

Adaptation
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Variety development
Tillage systems
New crop adoption: soybeans
Opening new lands
Irrigation equipment
Transportation system
Fertilizer adoption

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Table 6.1 Speed of adoption for some major agricultural adaptation measures

Adaptation	Adjustment time (yrs)	Reference
Variety adoption	3–14	Dalrymple, 1986; Griliches, 1957; Plucknett et al., 1987; CIMMYT, 1991.
Dams and irrigation	50–100	James and Lee, 1971; Howe, 1971.
Variety development	8–15	Plucknett et al., 1987; Knudson, 1988.
Tillage systems	10–12	Hill et al., 1994; Dickey et al., 1987; Schertz, 1988.
New crop adoption: soybeans	15–30	FAO, Agrostat – various years.
Opening new lands	3–10	Medvedev, 1987; Plusquellec, 1990.
Irrigation equipment	20–25	Turner and Anderson, 1980.
Transportation system	3–5	World Bank, 1994.
Fertilizer adoption	10	Pieri, 1992; Thompson & Wan; 1992.

Source: Adapted from Reilly (1995).

sense that it tells decision makers what to do. It does indicate directions where the in-depth analysis necessary for policy decisions can be fruitfully applied.

2 RELATED RESEARCH ON POSSIBLE RESPONSES TO CLIMATE CHANGE

Any thought of trying to mitigate against the speed or magnitude of global change must weigh the cost of mitigation against the potential harm, net of any adaptation which might be forthcoming, but including the cost of that adaptation. That is the point of integrated assessments, that attempt to integrate these factors together for global warming (Manne and Richels, 1992; Nordhaus, 1991, 1992, 1994; Yohe, 1993, 1994).

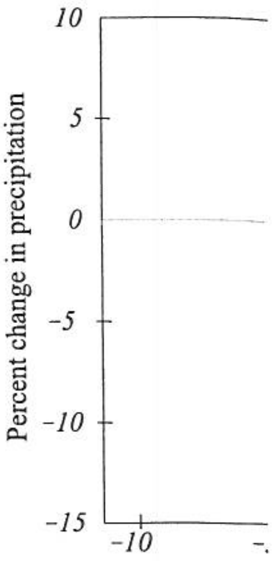
Research into the relative costs of various mitigation strategies has made great strides over the past few years (Gaskins and Weyant, 1993), but evaluation of the relative vulnerability, given potential adaptation, has lagged behind. Individual sectors have been studied, but there does not yet exist a consistent, organizational method with which to compare vulnerabilities across the extended time dimension of most global change phenomena.

A weakness of studies of the effects of climate change on agriculture is that they have focused on mean effects when higher order moments are also important (Schimmelpfennig, 1996). Agriculture depends on the specific realization of climate variables like temperature and precipitation that make up our weather. The random draw from the climate distribution that gives us our weather can come from the tails of the distribution. The vulnerability index we develop is a simple metric that summarizes all of the information by evaluating a series of points spread throughout the relevant distributions.

The details of this procedure are given in the Appendix, but the underlying idea can be illustrated graphically. To see how, consider some subset of real numbers A_0 defined to reflect variability in the current climate of some region expressed in terms of precipitation (denoted X) and temperature (Y). The set A_0 can be bounded, for the sake of simplicity but without loss of generality, by thinking of it as a confidence region of some predetermined level ($\varepsilon \cdot 100$ percent) for the current climate. Meanwhile, define a second set, B_{n0}, to reflect the viable region for some natural or engineered system (N), also expessed in terms of variability in precipitation and temperature. The notion here is that system N would be viable if X and Y were to occur within region B_{n0}, but that it would suffer severely if X and Y were to occur elsewhere.[1] The intersection of A_0 and B_{n0} represents a region of sustainability that can be expected to occur for system N with likelihood $\varepsilon \cdot 100$ percent. Probabilistically weighting these areas according to the techniques described in the Appendix places the value of the (area of) the intersection between zero and one and defines a 'sustainability index' that also lies between zero and one. The closer to one it is, the more secure is the existence of the system; the closer to zero, of course, the more likely it is that the system will expire. Defining a minimum value for this sustainability index is thus the functional equivalent of establishing a practical threshold of extinction.

Some systems may be close to that threshold, while others may not. Figures 6.1 and 6.2 show the difference. The left-hand side of Figure 6.1 shows a system with a relatively large portion of set A_0 covered by its B_{n0} region. If the density function were uniform, then $S_0(N)$ would appear to exceed 0.5 because the area of the intersection $A_0 \cap B_{n0}$ is greater than half the size of the climate set A_0. If the density function were to concentrate relatively more likelihood near the means of precipitation and temperature, of course, then $S_0(N)$ would be correspondingly higher.

Figures 6.2, 6.3 and 6.4 show, by way of contrast, systems whose regions of sustainability indices are small. In Figure 6.2, the index is small because the B_{n0} region is small and centered away from the means of temperature of precipitation A_0. In Figure 6.3, the B_{n0} straddles the means of A_0 well enough, but its orientation does not match the natural correlation of A_0. Uncorrelated variability finally swamps B_{n0} in Figure 6.4, where A_0 is enormous relative to B_{n0}. Finding any of these systems surviving their environments would be evidence that they have a low threshold of extinction. Some may be robust, but their low sustainability



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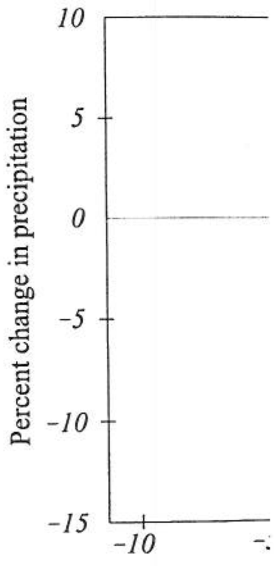

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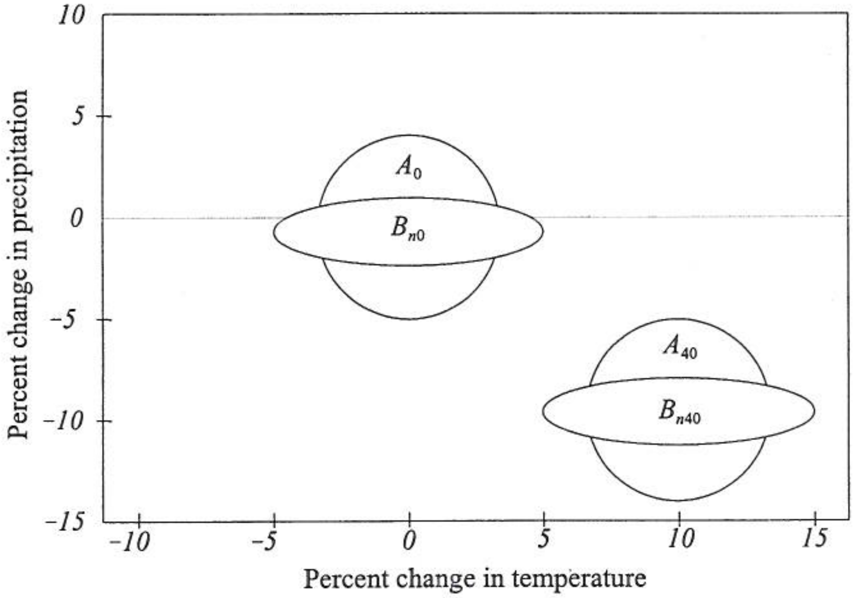


Figure 6.1 Sustainability indices represented by intersection of climate (A_0, A_{40}) and viability (B_{n0}, B_{n40})

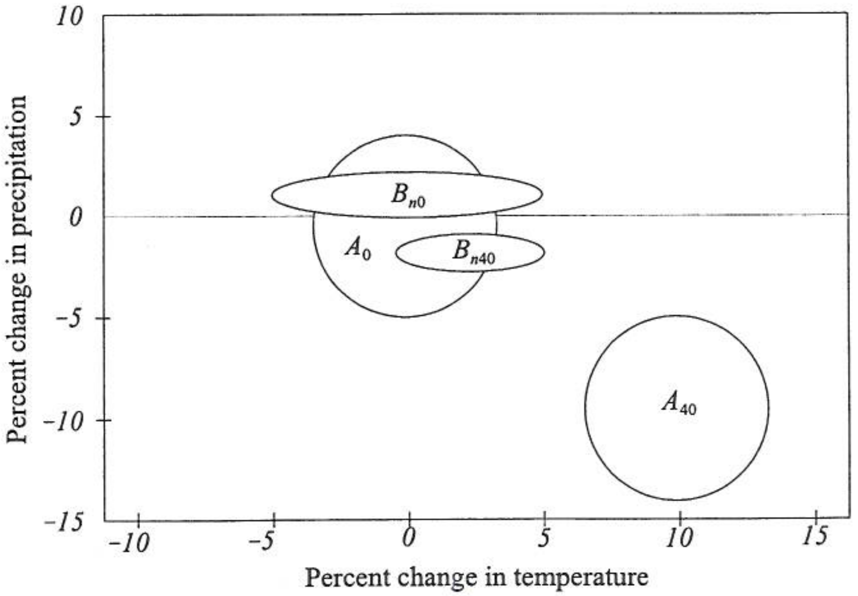


Figure 6.2 Smaller sustainability indices than represented in Figure 6.1

indices could indicate that their existence was, at best, very tenuous – marginal systems that might be threatened by even small climate change in the wrong direction.

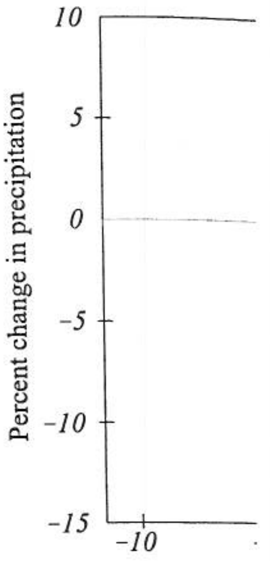
Figures 6.1 and 6.2 also show what might happen as the climate changes. Suppose that 40 years of climate change produced, for example, a new distribution of temperature and precipitation, denoted $f_{40}(X, Y)$. If only the means were to change, then set A_{40} would apply. If variability were to change, as well, then the shape of A_{40} would have changed, of course. The point here is simply that changing climate can be easily reflected by a migration of the associated confidence region.

Figure 6.1 shows what might happen if system *N* were to adapt perfectly as the climate changed. Notice that its region of sustainability has simply moved in synch with the climate so that the critical intersection, now between sets A_{40} and B_{n40}, is the same size. If the shift in climate were simply higher moment preserving shifts to a drier and warmer climate, though, neither the index of sustainability nor the index of vulnerability would change. Figure 6.5 shows a time trajectory for this fortunate case.

Figure 6.2 illustrates what might lie ahead as the climate changes for the less fortunate marginal system whose ability to adapt might be overwhelmed by the warmer and drier climate. The new climate region, A_{40}, does not intersect the new region of sustainability, B_{n40}, at all. The system quite simply must have perished well before the new climate was established. Figure 6.6 shows a time trajectory for this type of climate change extinction. It assumes that the climate changes over the course of 40 years but that the threshold of extinction is crossed after only 15 years. At that point, regions A_t and B_{nt} intersect with such low frequency that system collapse occurs precipitously.[2] Notice, too, that a similar trajectory would emerge from Figure 6.1 if the system had not adapted; region A_{40} does not intersect region B_{n0}.

Trajectories like the ones drawn in Figures 6.5 and 6.6 could be employed to calibrate adaptation options for aggressive, moderate and recalcitrant decision makers and political activists. Assuming a certain trajectory of climate change, a number of systems could be cataloged according to (1) the time they might cross their extinction thresholds absent adaptation and (2) the effectiveness of a range of adaptive responses. Comparisons of each might generate a robust list of 'vulnerability criteria' that could be applied beyond the set of specific examples studied. The timing scale on the horizontal axis could, of course, be stretched or contracted according to the speed with which people foresee climate changing. Timing sensitivity and sensitivity to various climate change scenarios could thereby be explored as well. This could allow decision makers to respond to threats on various systems on more than philosophical grounds.

The method outlined here is, above all else, designed to be practical. It recognizes the need for assessing vulnerability across a wide range of systems in support of planning processes that must assign priorities in allocating scarce resources to both the research and development of adaptive strategies and their



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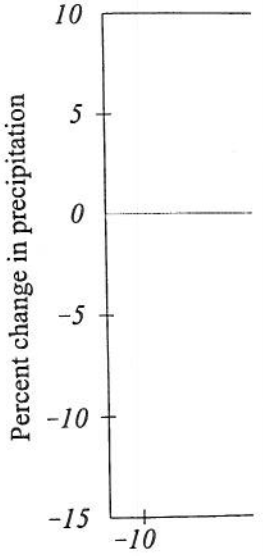

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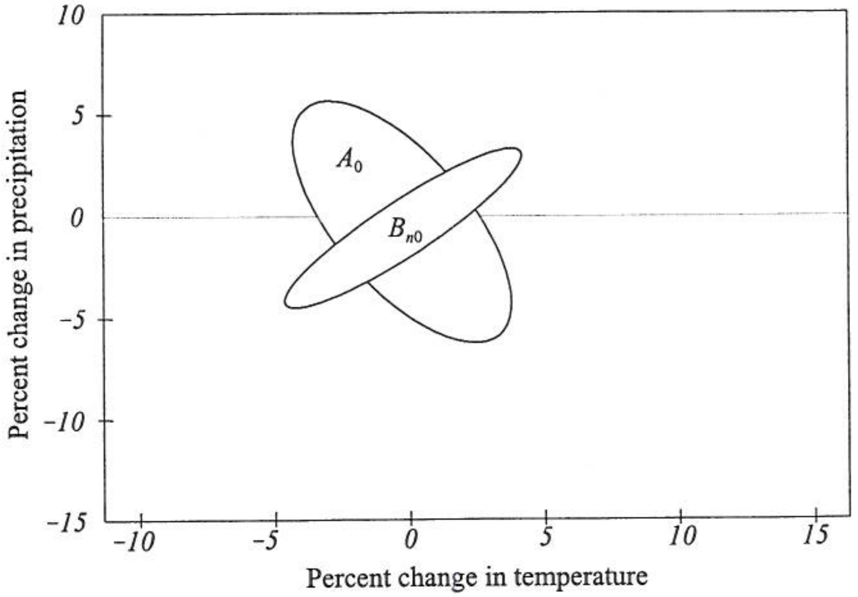

Figure 6.3 Mismatched climate (A_0) and viability (B_{n0})

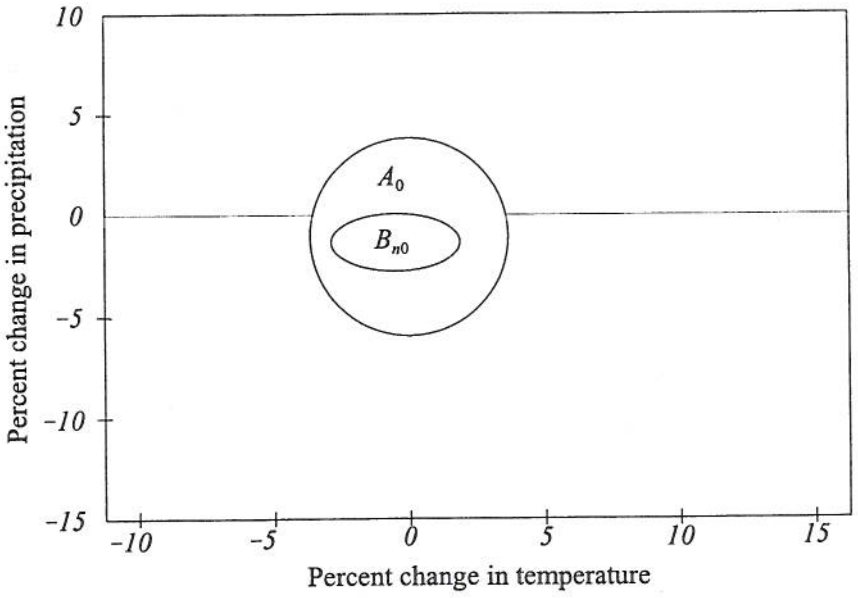

Figure 6.4 Climate (A_0) swamps viability (B_{n0})

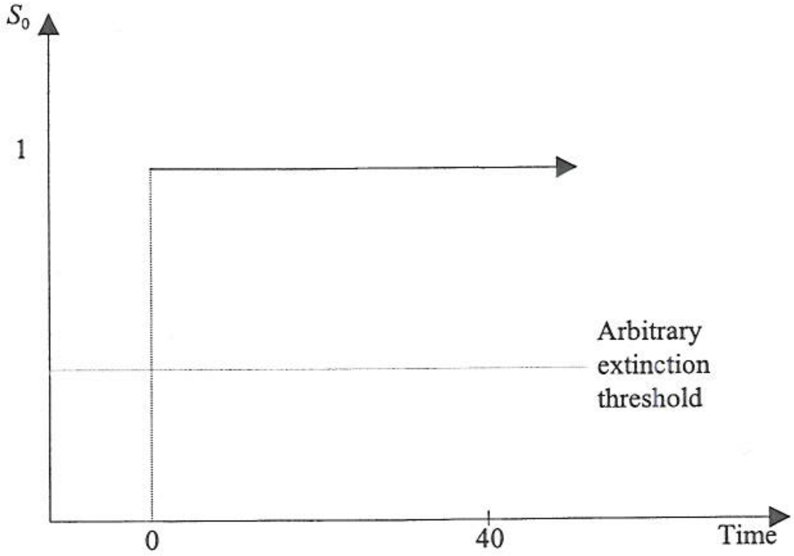

Figure 6.5 Sustainability index (S_0) above extinction level

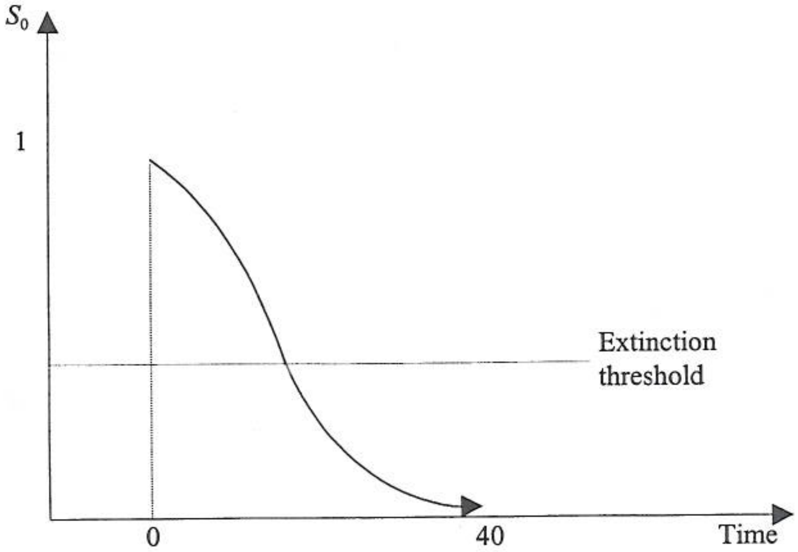

Figure 6.6 Extinction occurs after index (S_0) falls below threshold

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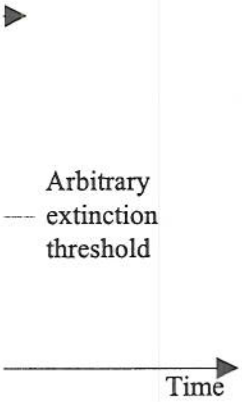

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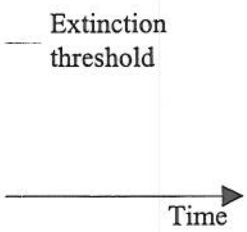

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implementation. It also recognizes that these judgements must be made in the context of large uncertainties and enormous time horizons. At the same time, though, it recognizes that the full range of quality data and theoretical tools that would be required to undertake complete and comprehensive analyses of vulnerable systems will not always be available. Indeed, the method is designed to apply simple and straightforward techniques to limited data to canvass a wide range of potentially vulnerable systems. This first step can help identify those systems where the collection of more complete data sets and the development of more comprehensive analytical tools will pay the largest dividends. The method developed here is, in short, deliberately 'low brow' and simplistic. It will not yield precise insights upon which policy and planning decisions can be made. It will, instead, support gross comparisons across disparate systems, like the major world agricultural crops, so that the long-term process of targeting various systems for detailed study will make as few errors of omission and commission as possible.

The next section gives a brief description of a simple statistical approach that can, with limited data, support the broad method outlined in the Appendix and applies the technique to selected crops throughout the world. Sections 3 and 4 turn to the issue of characterizing the future climate and the uncertainty with which we view it for these examples, allowing a means of tracking the index into the future. Section 5 concludes by drawing lessons from the illustrative applications. The notion that is developed is that there is more to tracking how and why vulnerability indices might change over time than simply positing a correlation with a plausible scenario for global mean temperature.

3 REPRESENTING CLIMATE VARIABILITY WITH DISCRETE DISTRIBUTIONS

The method outlined in the Appendix and to be implemented in this section requires several bits of information. First of all, useful representations of climate variability must be produced. In the notation of the Appendix, these are the A_i subsets. To that end, consider a collection of ordered pairs that reflect climate: deviations in temperature and precipitation around their mean, for example, which reflect the current climate. Represent the temperature and precipitation data by X and Y. Represent deviations around their means by x and y. The idea will be to identify a second, systematically chosen set of ordered pairs that can all be assigned the same probability but which nonetheless reflect the distribution of experience captured in the original data. A simple linear regression of y on x,

$$y_i = \alpha + \beta x_i + u_i, \qquad (6.1)$$

will be used to summarize the climate. Let

$$y = \alpha + \beta x \tag{6.2}$$

represent the estimated equation; the estimated intercept α must, of course, be constrained in the estimation process to equal zero.[3]

The procedure suggested here will work from the regression results to offer a discrete portrait of the resulting statistical summary of climate. It begins by producing a discrete representation of the underlying distribution for x – the independent variable for equation (6.1). Let $\{x_i\}$ support that representation with each $x_i \in \{x_i\}$ assigned probability p_i so that $\Sigma p_i = 1$, the mean $\Sigma p_i x_i = 0$, and the variance of x from the original sample is preserved. Elements in $\{x_i\}$ should be chosen so that $p_i = p$.

The next step produces similar representations of corresponding conditional distributions for y for each of the $x_i \in \{x_i\}$. Let $\{y_j(x_i)\}$ support these representations with each $y_j(x_i) \in \{y_j(x_i)\}$ to be assigned some probability p_j. The key is to choose the $y_j(x_i) \in \{y_j(x_i)\}$ so that it is possible to assign the same probability $p_j = p$ with $\Sigma p_j = 1$, the mean $\Sigma p_j\, y_j(x_i) = \beta x_i$, and the variance of the prediction error surrounding equation (6.1) given x_i preserved. The distribution of prediction error $y_i - \beta x_i$ can be characterized by

$$\{y - \beta x_i\} / s_u \{1 + [1/n] + [(x_i - \mu_x)^2 / \Sigma (x_j - \mu_x)^2]\}^{1/2} \sim t_{n\text{-}2}, \tag{6.3}$$

where $s_u^{\,2} = \{\Sigma [y_j - \beta x_j]^2\} / (n\!-\!2)$ is an unbiased estimate of the variance of the error term in equation (6.1) (Johnson, 1984).

The collection of ordered pairs $\{(x_i, y_j(x_i))\}$, all being assigned equal probability $p_{ij} = p^2$, can finally be proposed as a reasonable representation of the original climate data expressed in a way that can easily accommodate the calculation of a vulnerability index number – they are a workable representation of the necessary A_0 subset from the Appendix. Superimposing a climate response surface on a grid mapping of the pairs $\{(x_i, y_j(x_i))\}$ and counting the number of points that are not covered is then a practical and simple way to begin implementing the method of section 2. If m points are not covered, more specifically, the initial vulnerability index is simply mp^2.

A 25-Point Illustration

A joint distribution for (x, y) can be summarized by 25 equally probable ordered pairs if each of the conditional distributions rooted on five equally probable values of x_i are represented by five equally (conditionally) probable values of $y_j(x_i)$.

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)} support these representa-
robability p_j. The key is to
ign the same probability p_j
variance of the prediction
ıe distribution of prediction

$- \mu_x)^2]\}^{1/2} \sim t_{n-2},$ (6.3)

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; assigned equal probability
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ımber of points that are not
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5 equally probable ordered
ive equally probable values
probable values of $y_j(x_i)$.

Table 6.2 records the specifics of this case. The mean of the x values combines with the mean plus and minus $(.5)^{1/2}$ and $(2)^{1/2}$ times the estimated standard deviation of the x values to form the underlying discrete values for the $\{x_i\}$. Each can be given a probability of 0.2; as a set, they represent the 8th, 24th, 50th, 76th and 92nd percentiles of the original climate distribution for x.

Table 6.2 Specifics of a 25-point representation

Point value	Percentile
x_i:	
μ_x	50
$\mu_x \pm \sigma(0.5)^{1/2} = \mu_x \pm 0.71\sigma$	24 and 76
$\mu_x \pm \sigma(2.0)^{1/2} = \mu_x \pm 1.41\sigma$	8 and 92
$y_j(x_i)$:	
βx_i	50
$\beta x_i \pm \{s_u[1 + (1/n) + (x_i - \mu_x)]^2 / \Sigma (x_j - \mu_x)^2\} t_{n-2}\ (.24)$	24 and 76
$\beta x_i \pm \{s_u[1 + (1/n) + (x_i - \mu_x)]^2 / \Sigma (x_j - \mu_x)^2\} t_{n-2}\ (.08)$	8 and 92

Each of these x_i values can then be assigned a set of five conditional y_j values using the t-distribution for the percentiles identified above and the regression results from equation (6.2). The central value should be βx_i, of course. The four outside values are determined by βx_i plus or minus the denominator of the right-hand side of equation (6.3) multiplied by $t_{n-2}(.08)$ and $t_{n-2}(.24)$. Each conditional distribution assigns a probability of 0.2 to each $y_j(x_i)$, so each of the resulting 25 ordered pairs should be assigned probabilities of 0.04.

An 81-Point Illustration

Tables 6.3 and 6.4 repeat the process for 81 points, with nine x_i values and nine contingent $y_j(x_i)$ values for each x_i. Each ordered pair should therefore be assigned a probability of (1/81). Two alternatives are offered. The first moves along the range of x values uniformly and produces an equally uniform spread for the contingent y values. The other is based on a geometric spread which moves the third, fourth and fifth outside values away from the mean by factors of 2, 4 and 8 times the deviation of the second value from the mean. The alternatives may produce slightly different vulnerability indices in practice. When that is a problem, a finer grid of, say, 121 points might be more appropriate. Because the purpose is to provide gross representations of vulnerability to focus research and planning exercises, it is probably sufficient to average the two indices.

Table 6.3 Specifics of an 81-point representation – uniform spread

Point value	Percentile
x_i:	
μ_x	50
$\mu_x = \mu_x \pm 0.39\sigma$	35 and 65
$\mu_x = \mu_x \pm 0.78\sigma$	22 and 78
$\mu_x = \mu_x \pm 1.17\sigma$	12 and 88
$\mu_x = \mu_x \pm 1.56\sigma$	6 and 94
$y_j(x_i)$:	
βx_i	50
$\beta x_i \pm \{s_u[1 + (1/n) + (x_i - \mu_x)]^2 / \Sigma (x_j - \mu_x)^2\} t_{n-2}(.35)$	35 and 65
$\beta x_i \pm \{s_u[1 + (1/n) + (x_i - \mu_x)]^2 / \Sigma (x_j - \mu_x)^2\} t_{n-2}(.22)$	22 and 78
$\beta x_i \pm \{s_u[1 + (1/n) + (x_i - \mu_x)]^2 / \Sigma (x_j - \mu_x)^2\} t_{n-2}(.12)$	12 and 88
$\beta x_i \pm \{s_u[1 + (1/n) + (x_i - \mu_x)]^2 / \Sigma (x_j - \mu_x)^2\} t_{n-2}(.06)$	6 and 94

Table 6.4 Specifics of an 81-point representation – geometric spread

Point value	Percentile
x_i:	
μ_x	50
$\mu_x = \mu_x \pm 0.23\sigma$	42 and 58
$\mu_x = \mu_x \pm 0.46\sigma$	33 and 67
$\mu_x = \mu_x \pm 0.93\sigma$	18 and 82
$\mu_x = \mu_x \pm 1.85\sigma$	3 and 97
$y_j(x_i)$:	
βx_i	50
$\beta x_i \pm \{s_u[1 + (1/n) + (x_i - \mu_x)]^2 / \Sigma (x_j - \mu_x)^2\} t_{n-2}\ (.42)$	42 and 58
$\beta x_i \pm \{s_u[1 + (1/n) + (x_i - \mu_x)]^2 / \Sigma (x_j - \mu_x)^2\} t_{n-2}\ (.33)$	33 and 67
$\beta x_i \pm \{s_u[1 + (1/n) + (x_i - \mu_x)]^2 / \Sigma (x_j - \mu_x)^2\} t_{n-2}\ (.18)$	18 and 82
$\beta x_i \pm \{s_u[1 + (1/n) + (x_i - \mu_x)]^2 / \Sigma (x_j - \mu_x)^2\} t_{n-2}\ (.03)$	3 and 97

An Application – the U.S. Corn Belt

July is the critical month for determining the effect of precipitation and temperature on corn yields in the United States. It is the month that corn tassels form and is referred to as the heading month (Lawrence, 1986, Table V-I). Figure 6.7 displays precipitation and temperature data for the Corn Belt 'weighted by harvested cropland' as reported by the U.S. Department of Agriculture (USDA)

(Teigen and Singer, 1
equation (6.3). Table (
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Table 6.5 Discrete r

Percentage change in precipitation	
Uniform spread:	
45.2	1.18
33.9	1.29
22.6	1.42
11.3	1.56
0.0	1.71
-11.3	1.87
-22.6	2.05
-33.9	2.24
-45.2	2.44
Geometric spread:	
53.7	1.49
27.0	1.74
13.3	1.90
6.7	1.98
0.0	2.07
-6.7	2.17
-13.3	2.27
-27.0	2.49
-53.7	2.98

(Teigen and Singer, 1992). The sloped line is the corresponding estimate of equation (6.3). Table 6.5 records the results of applying the 81-point procedure outlined above to these data; notice that both the uniform and geometric spreads are reported.

Yield contours for corn in the United States are, meanwhile, available from the Research Directorate of the U.S. Department of Defense (DOD) (Lawrence, 1986). Figure 6.8 displays a 90 percent yield contour. Surveys of experts conducted by DOD determined that anticipated yields for corn in the U.S. are higher than 90 percent of the base-period expected yield for combinations of (1) deviations in the percentage change in precipitation around their mean and (2) deviations in temperature around its mean, on the inside of the contour. Superimposing this contour on the discrete representations of current climate recorded in Table 6.5 produces initial vulnerability indices (for 1990): 0.46 for the geometric spread and 0.23 for the uniform spread. A 0.345 average conforms to a sustainability index of 0.655.

This procedure is repeated below for the major crop-growing regions in the world. Historical data for temperature and precipitation in the crop-growing

Table 6.5 Discrete representations of current climate

Percentage change in precipitation	Temperature change								
Uniform spread:									
45.2	1.18	0.73	0.14	-0.19	-0.63	-1.07	-1.41	-1.99	-2.44
33.9	1.29	0.85	0.28	-0.04	-0.47	-0.90	-1.23	-1.80	-2.24
22.6	1.42	0.99	0.43	0.11	-0.32	-0.74	-1.06	-1.62	-2.05
11.3	1.56	1.13	0.58	0.26	-0.16	-0.57	-0.89	-1.45	-1.88
0.0	1.71	1.29	0.73	0.41	0.00	-0.41	-0.73	-1.29	-1.71
-11.3	1.87	1.44	0.89	0.57	0.16	-0.26	-0.58	-1.13	-1.56
-22.6	2.05	1.62	1.06	0.74	0.31	-0.11	-0.43	-0.99	-1.42
-33.9	2.24	1.80	1.23	0.90	0.47	0.04	-0.28	-0.86	-1.30
-45.2	2.44	1.99	1.41	1.07	0.63	0.19	-0.15	-0.73	-1.18
Geometric spread:									
53.7	1.49	0.33	-0.25	-0.51	-0.74	-0.98	-1.24	-1.83	-2.99
27.0	1.74	0.64	0.09	-0.15	-0.38	-0.60	-0.84	-1.40	-2.49
13.3	1.90	0.82	0.27	0.04	-0.19	-0.41	-0.65	-1.19	-2.27
6.7	1.98	0.91	0.37	0.13	-0.09	-0.32	-0.55	-1.09	-2.17
0.0	2.07	1.00	0.46	0.22	0.00	-0.22	-0.46	-1.00	-2.07
-6.7	2.17	1.09	0.55	0.32	0.09	-0.13	-0.37	-0.91	-1.98
-13.3	2.27	1.19	0.65	0.41	0.19	-0.04	-0.27	-0.82	-1.90
-27.0	2.49	1.39	0.84	0.60	0.38	0.15	-0.09	-0.65	-1.74
-53.7	2.98	1.83	1.24	0.99	0.75	0.51	0.25	-0.33	-1.50

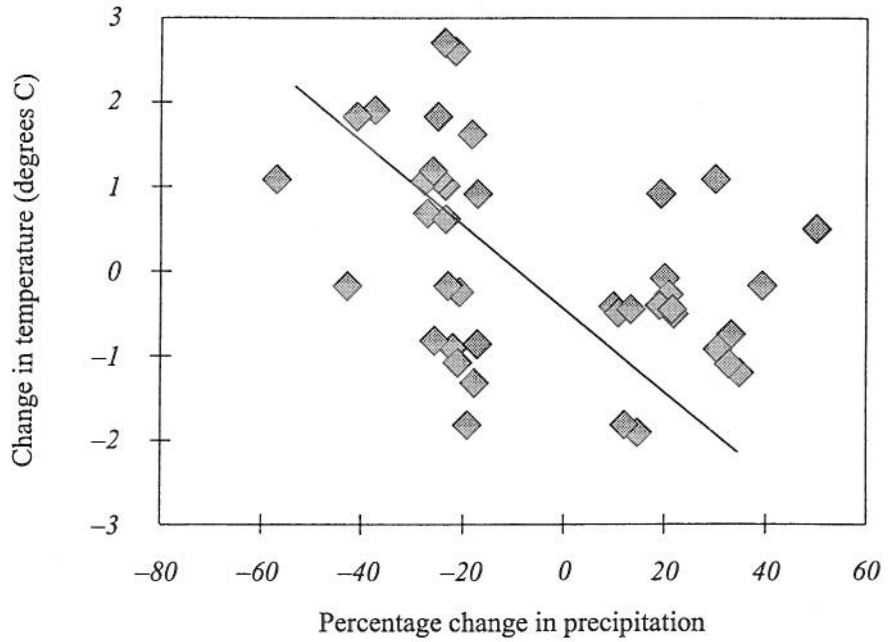

Figure 6.7 Actual climate for U.S. Corn Belt

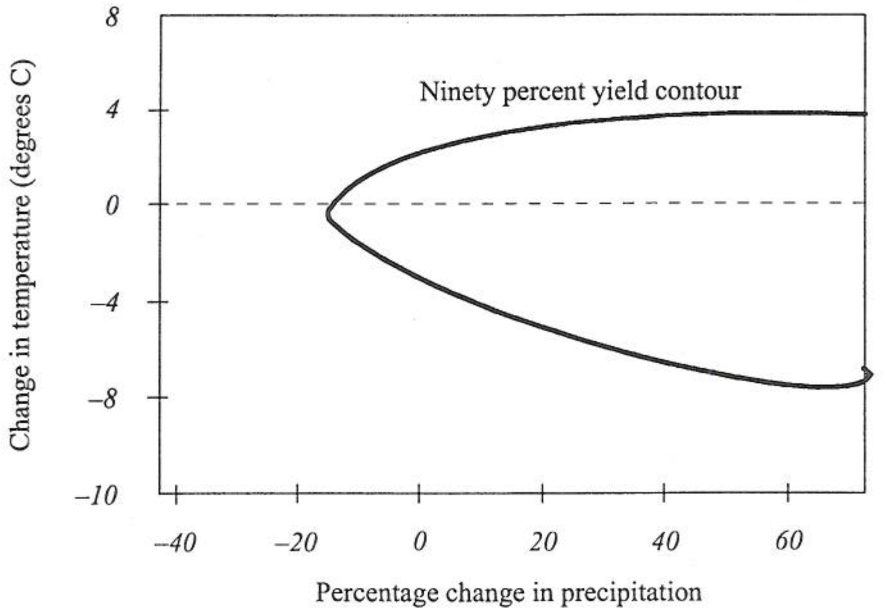

Figure 6.8 Actual viability for U.S. corn

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4 IMPOSING FU GLOBE

Projecting vulnerability
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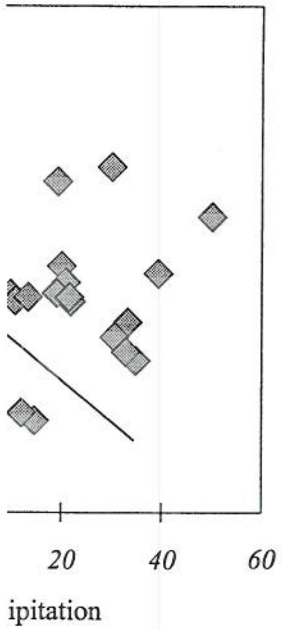

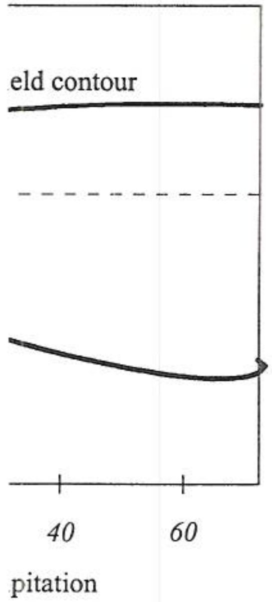

regions of the United States are available in several formats from USDA. Descriptions of the world growing regions are also available in Strommen (1994). This USDA publication with specific detail about crop locations allows us to select weather data from over 6,000 weather stations that give the longest temperature and precipitation records in the appropriate region for an individual crop. Precipitation records are often longer than temperature records, and for several cases, our data are continuous from the 1800s. The world weather data are available on CD-ROM (Vose et al., 1992).

U.S. corn yields are sensitive to the variability of the historical temperature record from 1950 to 1990 in the Corn Belt. This explains why U.S. corn yields have followed long-term boom and bust cycles. The overall trend in yield has been positive, but the long-term trajectory has tended to mask variability. Yield fell by 2.02 metric tonnes/hectare (MT/ha) or 28 percent between 1982 and 1983, 2.21 MT/ha or 29 percent between 1987 and 1988, and 1.93 MT/ha or 23 percent between 1992 and 1993 (Hazell, 1984; Webb and Gudmunds, 1992). This variability in corn production in the Midwest is captured by the method proposed here as a measure of vulnerability. A low sustainability index or a high vulnerability index indicates a greater susceptibility to the extreme weather events in the tails of the weather distribution.

4 IMPOSING FUTURE CLIMATE CHANGE ACROSS THE GLOBE

Projecting vulnerability indices into the future requires that trajectories of temperature change and precipitation patterns be specified; and it would be most useful if these specifications could accommodate variability in both the natural environment and the international policy arena. There are undoubtedly huge uncertainties associated with both estimates of future climate and policy responses, so we diversify our approach to characterizing the future. First we project vulnerability indices into the future based on regional results from Global Circulation Models (GCMs).

As part of the IPCC Working Group II's effort to make the assessments of different authors on different aspects of the climate change problem comparable, Greco et al. (1994) produced regional results from several GCMs and made them available to the Second Assessment Report lead authors. We use their unpublished transient, coupled ocean-atmosphere GCM results from the Geophysical Fluid Dynamics Laboratory (GFDL) for 2050 and 2100 in each of the appropriate crop-growing regions. The method is the same as before. The only difference is that the temperature and precipitation distributions like the ones in Table 6.5 for the Corn Belt are no longer centered at zero change in temperature and zero percentage change in precipitation on the yield contour graph; they are, instead, shifted by the predicted change in temperature and precipitation from the GCM. The distribution is shifted twice, once for the predicted change in 2050 and again for 2100, and sustainability indices are recalculated each time. Sustainability indices for major world food crops are reported for 1990, 2050 and 2100 in Table 6.6.

Most of the sustainability indices reported in Table 6.6 do not deteriorate significantly under the future climate predicted by the GFDL GCM. Indeed, some even improve. This is because the GFDL model generally predicts increases in precipitation that offset the effects on crop yields of predicted increases in temperature. So the effect of climate change on yield is not pronounced even in the absence of any adaptation.

Table 6.6 Future sustainability indices for major world food crops, based on GFDL climate scenario

	1990	2050	2100
Russia winter wheat	0.87	0.87	0.94
Canada spring wheat	0.85	0.84	0.89
Australia winter wheat	0.83	0.83	0.83
Russia spring wheat	0.79	0.77	0.88
Argentina corn	0.79	0.82	0.85
U.S. winter wheat	0.75	0.78	0.75
Brazil soybeans	0.73	0.90	0.95
Argentina winter wheat	0.71	0.65	0.69
China rice	0.68	0.74	0.70
U.S. soybeans	0.68	0.64	0.81
U.S. spring wheat	0.68	0.85	0.84
China winter wheat	0.67	0.72	0.89
U.S. corn	0.66	0.64	0.79
India winter wheat	0.65	0.63	0.56
India rice	0.41	0.17	0.43

Note: The GFDL model generally predicts increases in both temperature and precipitation.

Adaptation needs to be considered especially (but not exclusively) if the anticipated increase in precipitation does not materialize. The index suggested here can accommodate some of the more obvious possibilities. Crop migration may, for example, be one way that agriculture might adapt to future climate change. Crops might then continue to be grown in climates with temperature patterns that closely match their current environments. Preliminary insight into the potential success of this sort of planned migration can be supported by the indexing method suggested here. It is enough to replace the home region's future climate distribution with the future distribution from another region to produce a sustainability index *cum* migration.

Could future corn production, for example, migrate profitably under future climate regimes into regions where spring wheat is presently being grown?

Computing a sustainabilit
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e profitably under future presently being grown?

Computing a sustainability index *cum* migration for this move suggests that this is, indeed, an idea worth considering. Moving corn production to a northern spring wheat-growing region shows that its sustainability index would rise from .66 to .72 under the present climate. More importantly, the index would rise from .64 to .85 in 2050 and from .79 to .84 in 2100. Even with favorable changes in precipitation patterns, the sustainability ranking of U.S. corn would, in the *ceteris paribus* context of Table 6.6, climb from thirteenth to eighth in 1990, from thirteenth to second in 2050 and from tenth to seventh in 2100.[4] More detailed analysis of opportunity cost, conducted within the full spectrum of alternative adaptive strategies, would be required to conclude that corn should be expected to be grown in the northern United States as the climate changes. These preliminary results do, at least, suggest that such analysis should include corn in the set of alternatives for the northern United States. Indeed, systematic application of the indexing method might fill in a sizeable portion of that set.

Turning finally to explore how changes in abatement policy might influence vulnerability, consider the time trajectories of global mean temperature that emerge from integrated assessment models – models that can accommodate wide ranges of mitigating policy intervention. Objection will certainly be raised that temperature change in the middle of the United States need not match the global mean, and that criticism is fair. It should be expected, however, that temperature change in the Midwest should at least be *correlated* with change in the global mean. It should therefore be a simple matter to adjust the regional temperature trajectory once that correlation is deduced and thereby maintain an important link to the effect of mitigating policies. One question remains, though: is calibrating that correlation enough?

Table 6.7 records three different global mean temperature trajectories that emerge from the baseline runs of some recent integrated assessment modeling conducted by Yohe (1991, 1994) – a modeling exercise that weds the probabilistic aggregate production structure of Nordhaus and Yohe (1983) with the integrating structure of Nordhaus' DICE framework (Nordhaus, 1992, 1994).[5] The second column reflects the unregulated trajectory. The third reflects the temperature trajectory that emerges when carbon emissions are optimally regulated (subject to informational constraints on decision makers over time). The fourth reflects the temperature trajectory that emerges when carbon emissions are sub-optimally restricted to a cumulative total equal to 20 percent of the unregulated total through the year 2100.[6]

Tables 6.8 and 6.9 record sustainability indices, averaged across the uniform and geometric spreads, for the 90 percent Corn Belt yield contour that correspond to the unrestricted and the 20 percent emissions reduction temperature trajectories under two sets of assumptions. The second temperature trajectory is omitted because the underlying 3.6 percent reduction in cumulative emissions through the year 2100 make so little difference relative to the unrestricted case. In the first, only the mean temperature changes along the indicated global mean trajectory

Table 6.7 Global mean temperature trajectories based on Yohe (1991, 1994)

Year	No regulation	Optimal regulation	20 percent emission reduction
1975	0.44	0.44	0.44
1990	0.93	0.93	0.93
2000	1.21	1.21	1.20
2010	1.47	1.47	1.45
2020	1.72	1.71	1.67
2030	1.97	1.95	1.89
2040	2.21	2.18	2.09
2050	2.43	2.39	2.29
2060	2.65	2.60	2.46
2070	2.85	2.80	2.62
2080	3.03	2.97	2.76
2090	3.20	3.13	2.88
2100	3.34	3.28	2.97

Table 6.8 Sustainability indices for U.S. corn along the unrestricted emissions trajectory

Year	Temperature change only	Temperature change with precipitation reduction
1975	0.66	0.66
1990	0.63	0.54
2000	0.61	0.50
2010	0.58	0.46
2020	0.56	0.41
2030	0.53	0.35
2040	0.51	0.31
2050	0.48	0.26
2060	0.43	0.24
2070	0.42	0.20
2080	0.38	0.18
2090	0.35	0.17
2100	0.32	0.14

Note: Results are based on climate change scenarios from Yohe (1991, 1994).

while the annual variability in temperature and precipitation that is reflected in Table 6.5 is preserved. In the second, the variability of Table 6.5 is still preserved, but precipitation falls steadily as the mean temperature rises so that, by 2050, average precipitation will have fallen by 20 percent.

Several points become clear from even brief consideration of Tables 6.8 and 6.9. The sustainability index falls discernibly in all cases, but the fall is more dramatic when changes in temperature are accompanied by reductions in rainfall.

Table 6.9 Sustainab
reduction

Year	Temperat
1975	
1990	
2000	
2010	
2020	
2030	
2040	
2050	
2060	
2070	
2080	
2090	
2100	

Note: Results are base

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5 CONCLUDIN

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strategies should be s
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20 percent emission reduction
0.44
0.93
1.20
1.45
1.67
1.89
2.09
2.29
2.46
2.62
2.76
2.88
2.97

g the unrestricted emissions

mperature change with ecipitation reduction
0.66
0.54
0.50
0.46
0.41
0.35
0.31
0.26
0.24
0.20
0.18
0.17
0.14

m Yohe (1991, 1994).

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f Table 6.5 is still preserved,
ature rises so that, by 2050,

sideration of Tables 6.8 and
l cases, but the fall is more
ied by reductions in rainfall.

Table 6.9 Sustainability indices for U.S. corn along a 20 percent emission reduction trajectory

Year	Temperature change only	Temperature change with precipitation reduction
1975	0.66	0.66
1990	0.63	0.54
2000	0.61	0.50
2010	0.58	0.46
2020	0.56	0.39
2030	0.54	0.37
2040	0.52	0.33
2050	0.49	0.29
2060	0.47	0.26
2070	0.44	0.24
2080	0.43	0.21
2090	0.40	0.19
2100	0.39	0.18

Note: Results are based on climate change scenarios from Yohe (1991, 1994).

This is not a surprise. Perhaps more surprising is the recognition that moving to a 20 percent emissions reduction trajectory has so little effect even when agriculture appears to be so vulnerable. If a 50 percent reduction in the sustainability index were determined to be a measure of the critical level for the commercial viability of growing corn, for example, then a 20 percent reduction in cumulative emissions would buy only an extra ten years of viability along the temperature and precipitation trajectory. This small effect is surely rooted in the fact that the yield contours reflect absolutely no adaptation to climate change in the way farmers grow corn. In terms of the planning function that this indexing method is designed to inform, then, Tables 6.8 and 6.9 surely highlight adaptation in corn farming as a likely target for productive and worthwhile consideration.

5 CONCLUDING REMARKS

Beyond the creation of a simplistic and practical indexing method designed explicitly to help planners distinguish across a wide range of systems that might be vulnerable to climate change, this chapter offers two insights that can be drawn from its agriculturally based illustrations. First, the full range of possible adaptive strategies should be surveyed even if the climate change news does not turn out to be so bad. Change will, in such cases, be more of a purveyor of opportunity than carrier of trouble. But the economic cost of missing an opportunity to improve can be every bit as large as the cost incurred by failing to respond to a problem. Good news does not, therefore, diminish the potential value of a practical method for assessing vulnerability to change.

It is true that an index of vulnerability of farm profits, rather than the index of crop yield vulnerability presented here, would provide more information in support of policy decisions. Unfortunately it is not possible to sign the effect of changes in yield vulnerability on farm profits. An example makes it clear why this is so. Let farm profits (π) be the difference between revenue and cost. Revenue is made up of output price (p), acres planted (A) and yield per acre (y). Cost is a function of A, which is independent of the yield vulnerability index. This assumption is only true if the prices of inputs like fertilizer, seed and irrigation water are not affected by climate change. The derivative of farm profits with respect to the index is:

$$\frac{d\pi}{d\ index} = \frac{dp}{d\ index}\ Ay + pA\ \frac{dy}{d\ index}. \tag{6.4}$$

We would like to be able to sign the first term. This requires that the signs on the other two derivative terms be the same. The derivative of output with respect to the index is negative because the higher the yield vulnerability index the lower the output. The derivative of the price with respect to the index can be positive or negative.

If an individual farm supplied the entire market for an agricultural crop, the higher the level of output the lower the price would be with normal downward sloping demand. Some studies have assumed this is the case (Kaiser et al., 1992). It is plausible, however, that climate change will not affect all world agriculture the same, and that there may be regional differences in the effects on one commodity. This is why we developed a different vulnerability index for each crop in each region. If output rises in one region and falls in another, international trade effects and differences in the market power of different countries will determine the net effect of a change in the vulnerability index on the world price of a commodity. What is driving the change in the index is a change in climate and this change may not affect the indices equally around the world, so the effect on world price is indeterminate and it is not possible to sign the left-hand side of equation (6.4). Even if the index were affected by climate change in the same way throughout the world, and a decrease in yield were accompanied by an unequivocal increase in world price, the effect on farm profits would still be indeterminate. There might also be scale effects where profits rise for small decreases in yield (the price effect dominates) but fall for large decreases in yield (the output effect dominates). Abstracting from farm programs and other institutions that affect farm profits, price and yield are going in opposite directions and profits could go up or

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APPENDIX

This section outlines
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Let $f_0(X, Y)$ be the

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revenue and cost. Revenue is
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seed and irrigation water are
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$$A \quad \frac{dy}{d \ index}. \qquad (6.4)$$

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down. It is therefore inadvisable to draw any conclusion about changes in farm profits from changes in the yield index.

Secondly, and perhaps most importantly, comparing the sustainability trajectories recorded in Tables 6.8 and 6.9 with the corn sustainability estimates offered for 2050 and 2100 in Table 6.6 clearly shows that tracking temperature change is not enough to completely describe the future effects of global climate change. Precipitation clearly matters, not only in distinguishing the role to be played by adaptation, but also in defining size and even the direction of the effect. This observation is not a new insight by any means. Yet, most of the integrated assessment exercises being conducted by researchers around the world use only temperature to link emissions of greenhouse gases and their associated atmospheric concentrations with the economic cost of the physical and biological impacts of global climate change. This is a practice whose validity must continue to be questioned until it is shown that future regional temperature patterns can be sufficiently correlated both with the trajectories of other critical variables *and* with the global mean, to assert that a unidimensional impact index like global mean temperature captures enough of the variance to be useful.

APPENDIX

This section outlines steps to create an index of vulnerability of economic or natural systems within the current environment and vulnerability to change in that environment. Let A_0 reflect variability in the current climate of some region expressed in terms of X and Y. Let A_0 be a confidence region of some predetermined level ($\varepsilon \cdot 100$ percent) for the current climate. Define a second set, B_{n0}, to reflect the viable region for some natural or engineered system (N), also expressed in terms of variability in precipitation and temperature. As noted in the text, system N would be viable if X and Y were to occur within region B_{n0}, but would suffer severely if X and Y were to occur elsewhere. The intersection of A_0 and B_{n0} represents a region of sustainability which can be expected to occur for system N with likelihood $\varepsilon \cdot 100$ percent.

Let $f_0(X, Y)$ be the probability density function which defines set A_0 so that:

$$\int_A f_0(X, Y)dX\,dY = \varepsilon, \qquad (A.1)$$

$$\int_A X f_0(X, Y)dX\,dY = 0, \qquad (A.2)$$

$$\int_{A} Y f_0(X,Y)dX\,dY = 0, \tag{A.3}$$

where ε is very small. The index of sustainability for system N in the current climate, $S_0(n)$, can now be suggested:

$$S_0(N) \equiv \{\int_{A_0 \cap B_{n0}} f_0(X, Y)dX\,dY\} \,/\, \{\int_{A_0} f_0(X, Y)dX\,dY\} \tag{A.4}$$

$$= \{\int_{A_0 \cap B_{n0}} f_0(X,Y)dXdY\} \,/\, \varepsilon \tag{A.5}$$

A corresponding index of vulnerability,

$$V_0(N) \equiv [1 - S_0(N)], \tag{A.6}$$

may prove to be more instructive. For each system a minimum value for the sustainability index might be established to indicate a threshold of extinction. Finding a value below this threshold would cause the index of vulnerability to climb to one over the near term while the index of sustainability would fall to zero.

NOTES

1. Issues of exposure to environmental stress are germane, here. The sustainability of a system might suffer after a single episode beyond the boundaries of B_{n0} or it may require repeated and/or successive episodes. The discussion presented in this approach will assume the former case. Requirements for prolonged exposure to stress could probably be handled by adjusting the definition A_0 to reflect likelihood of multiple episodes. This is, of course, a theoretical question which must be overcome in the process of creating a detailed structure for this method.
2. This defines both threshold and dynamics of collapse. The literature has little if anything to present in terms of a consistent method for indexing vulnerability. The early contributions to what will undoubtedly grow to be a substantial literature on biodiversity have begun to appear in print (Weitzman, 1992; Solow et al., 1993).
3. Recall that y and x both represent deviations around the means of the original data, Y and X.
4. It is perhaps most interesting to note that the index for corn in North Dakota ranks higher than winter wheat in 2050 and falls just short in 2100.
5. These runs are based upon a Cobb–Douglas aggregate production function in labor, capital, fossil fuel and non-fossil fuel with a wide range of random variables and parameters assigned their median values. Future applications will create Monte Carlo simulation results over all of those sources of uncertainty in the context of aggregate production which accommodates, at least in year to year approximation, non-unitary elasticities of substitution between fossil and non-fossil fuels *and* between energy and labor and capital. See Yohe (1984) for the approximation procedure.

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6. This restriction is acc
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rate of interest.

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$(X, Y)dX\, dY\}$ (A.4)

(A.5)

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Carlo simulation results over all of
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See Yohe (1984) for the approxima-

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6. This restriction is accomplished by a two-part carbon tax. The first part reflects the perceived marginal damage of emissions; the second adds a scarcity rent which grows at the underlying rate of interest.

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