The Impact of Global Warming on Agriculture: A Ricardian Analysis

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We measure the economic impact of climate on land prices. Using cross-sectional data on climate, farmland prices, and other economic and geophysical data for almost 3,000 counties in the United States, we find that higher temperatures in all seasons except autumn reduce average farm values, while more precipitation outside of autumn increases farm values. Applying the model to a global-warming scenario shows a significantly lower estimated impact of global warming on U.S. agriculture than the traditional production-function approach and, in one case, suggests that, even without CO_2 fertilization, global warming may have economic benefits for agriculture. (*JEL* Q10, Q25)

Over the last decade, scientists have extensively studied the greenhouse effect, which holds that the accumulation of carbon dioxide (CO_2) and other greenhouse gases (GHG's) is expected to produce global warming and other significant climatic changes over the next century. Numerous studies indicate major impacts on agriculture, especially if there is significant mid-continental drying and warming in the U.S. heartland.[1] Virtually every estimate of economic impacts relies on a technique we denote the production-function approach.

This study compares the traditional production-function approach to estimating the impacts of climate change with a new "Ricardian" approach that examines the impact of climate and other variables on land values and farm revenues. The traditional approach to estimating the impact of climate change relies upon empirical or experimental production functions to predict environmental damage (hence its label in this study as the production-function approach).[2] This approach takes an underlying production function and estimates impacts by varying one or a few input variables, such as temperature, precipitation, and carbon dioxide levels. The estimates might rely on extremely carefully calibrated crop-yield models (such as CERES or SOYGRO) to determine the impact upon yields; the results often predict severe yield reductions as a result of global warming.

While providing a useful baseline for estimating the impact of climate change on farming, these studies have an inherent bias and will tend to overestimate the damage. This bias is sometimes called the "dumb-farmer scenario" to suggest that it omits a

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[1]See particularly the reports of the Intergovernmental Panel on Climate Change (1990) and the National Academy of Sciences Panel on Greenhouse Warming (1992).

[2]Important studies include John Callaway et al. (1982), W. Decker et al. 1986, Richard Adams et al. (1988, 1990), Adams (1989), D. Rind et al. (1990), and Cynthia Rosenzweig and Martin L. Parry (1994). For useful surveys, see National Research Council (1983), Joel Smith and Dennis Tirpak (1989), National Academy of Sciences (1992), and William Cline (1992).

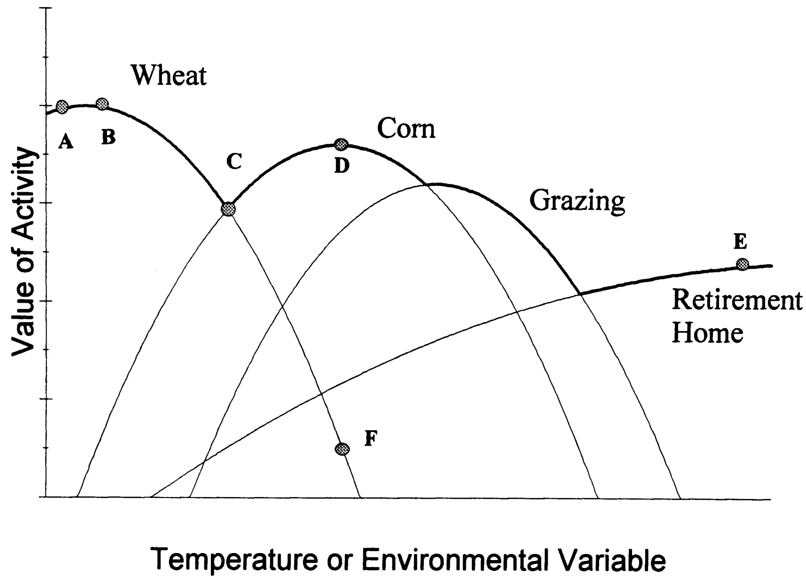

FIGURE 1. BIAS IN PRODUCTION-FUNCTION STUDIES

variety of the adaptations that farmers customarily make in response to changing economic and environmental conditions. Most studies assume little adaptation and simply calculate the impact of changing temperature on farm yields. Others allow limited changes in fertilizer application, irrigation, or cultivars (see William Easterling et al., 1991). None permits a full adjustment to changing environmental conditions by the farmer. For example, the literature does not consider the introduction of completely new crops (such as tropical crops in the south); technological change; changes in land use from farming to livestock, grassland, or forestry; or conversion to cities, retirement homes, campsites, or the 1,001 other productive uses of land in a modern postindustrial society.

By not permitting a complete range of adjustments, previous studies have overestimated damages from environmental changes. Figure 1 shows the hypothetical values of output in four different sectors as a function of a single environmental variable, temperature, in order to illustrate the general nature of the bias. In each case, we assume that the production-function approach yields an accurate assessment of the economic value of the activity as a function of temperature. The four functions provide a simplified example of how the value of wheat, corn, grazing, and retirement homes might look as a function of the temperature. For example, the curve to the far left is a hypothetical "wheat production function," showing how the value of wheat varies with temperature, rising from cold temperatures such as point A, then peaking at point B, finally falling as temperatures rise too high. A production-function approach would estimate the value of wheat production at different temperatures along this curve.

The bias in the production-function approach arises because it fails to allow for economic substitution as conditions change. For example, when the temperature rises above point C, adaptive and profit-maximizing farmers will switch from wheat to corn. As temperature rises, the production-function approach might calculate that the yield has fallen to F in wheat, but wheat is in reality no longer produced; the realized value is actually much higher, at point D where corn is now produced. At a slightly higher temperature, the land is no longer optimally used for corn but switches to grazing, and production-function estimates that do not allow for this conversion will again overestimate the losses from climate change. Finally, at point E, even the best agricultural model will predict that the land is unsuitable for farming or grazing and that the damage is severe. A more complete approach might find that the land has been converted to retirement villages, to which old folks flock so they can putter around in the warm winters and dry climates.

All this is of course illustrative. However, it makes the crucial point that the production-function approach will overestimate the damages from climate change because it does not, and indeed cannot, take into account the infinite variety of substitutions, adaptations, and old and new activities that may displace no-longer-advantageous activities as climate changes.

In this study, we develop a new technique that in principle can correct for the bias in the production-function technique by using economic data on the value of land. We call this the *Ricardian approach*, in which, instead of studying yields of specific crops, we examine how climate in different places affects the net rent or value of farmland. By directly measuring farm prices or revenues, we account for the direct impacts of climate on yields of different crops as well as the indirect substitution of different inputs, introduction of different activities, and other potential adaptations to different climates. If markets are functioning properly, the Ricardian approach will allow us to measure the economic value of different activities and therefore to verify whether the economic impacts implied by the production-function approach are reproduced in the field.

The results of the Ricardian approach can be seen in Figure 1. We assume that the "value" measured along the vertical axis is the net yield per acre of land; more precisely, it is the value of output less the value of all inputs (excluding land rents). Under competitive markets, the land rent will be equal to the net yield of the highest and best use of the land. This rent will in fact be equal to the heavy solid line in Figure 1. We label the solid line in Figure 1 the "best-use value function."

In general, we do not observe market land rents because land rent is generally a small component of the total profits. However, with farms, land rents tend to be a large fraction of total costs and can be estimated with reasonable precision. Farm value is the present value of future rents, so if the interest rate, rate of capital gains, and capital per acre are equal for all parcels, then farm value will be proportional to the land rent. Therefore, by observing the relationship of farm values to climatic and other variables, we can infer the shape of the solid, best-use value function in Figure 1.[3]

This study measures the effect of climatic variables on agriculture. We examine both climatic data and a variety of fundamental geographical, geophysical, agricultural, economic, and demographic factors to determine the intrinsic value of climate on farmland. The units of observation are U.S. counties in the lower 48 states. We examine the effect of climatic variables as well as nonclimatic variables on both land values and farm revenue, and the analysis includes a number of urban variables in order to measure the potential effect of development upon agricultural land values. The analysis suggests that climate has a systematic impact on agricultural rents through temperature and precipitation. These effects tend to be highly nonlinear and vary dramatically by season. The paper concludes with a discussion of the impacts of global warming on American farms.

I. Measuring the Effect of Climate on Agriculture

Using the Ricardian technique, we estimate the value of climate in U.S. agriculture. Agriculture is the most appealing application of the Ricardian technique both because of the significant impact of climate

[3]The analytical basis for the present empirical study is presented in Mendelsohn et al. (1993).

on agricultural productivity and because of the extensive county-level data on farm inputs and outputs.

Sources and Methods

The basic hypothesis is that climate shifts the production function for crops. Farmers at particular sites take environmental variables like climate as given and adjust their inputs and outputs accordingly. Moreover, we assume perfect competition in both product and input markets. Most important, we assume that the economy has completely adapted to the given climate so that land prices have attained the long-run equilibrium that is associated with each county's climate.

For the most part, the data are actual county averages, from the *1982 U.S. Census of Agriculture*, so that there are no major issues involved in obtaining information on these variables.[4] The *County and City Data Book* (U.S. Bureau of the Census, 1988) and the computer tapes of those data are the sources for much of the agricultural data used here, including values of farm products sold per acre, farm land and building values,[5] and information on market inputs for farms in every county in the United States. In addition, in many specifications, we include social, demographic, and economic data on each of the counties; these as well are drawn from the *County and City Data Book*.

Data about soils were extracted from the National Resource Inventory (NRI) with the kind assistance of Daniel Hellerstein and Noel Gollehon of the U.S. Department of Agriculture. The NRI is an extensive survey of land characteristics in the United States. For almost 800,000 sites, NRI has collected soil samples, or land characteristics, each providing a measure of salinity, permeability, moisture capacity, clay content, sand content, flood probability, soil erosion (K-factor), rain erosion (R-factor), slope length, wind erosion, whether or not the land is a wetland, and numerous other variables that are not used in this analysis. Each sample also contains an expansion factor, which is an estimate of the amount of land the sample represents in that county. Using these expansion factors, we aggregate these data to yield an overall county estimate for each soil variable.

Climatic data pose more difficult issues. They are available by meteorological station rather than by county, so it was necessary to estimate county-average climates. To begin with, climate data were obtained from the National Climatic Data Center, which gathers data from 5,511 meteorological stations throughout the United States. These stations form a dense set of observations for most regions of the United States, with the exception of some of the desert Southwest. The data include information on precipitation and temperature for each month from 1951 through 1980. Since the purpose of this study is to predict the impacts of climate changes on agriculture, we focus on the long-run impacts of precipitation and temperature on agriculture, not year-to-year variations in weather. We consequently examine the "normal" climatological variables —the 30-year average of each climatic variable for every station. In this analysis, we collect data on normal daily mean temperature and normal monthly precipitation for January, April, July, and October. We focus on these four months in order to capture seasonal effects of each variable. For example, cold January temperatures may be important as a control on insect pests, warm-but-not-hot summers may be good for crop growth, and warm October temperatures may assist in crop harvesting.

In order to link the agricultural data which are organized by county and the climate data which are organized by station, we conduct a spatial statistical analysis that examines the determinants of the climate of each county. Although the specific climatic variables we analyze in this study have been measured frequently, there are some counties with no weather stations and others with several. Some of the weather stations

[4]Appendix A contains complete descriptions and definitions of the variables used in this study.

[5]The definition and source of the farm value variable is critical to this study, and its derivation is described in Appendix B.

TABLE 1—INTERPOLATION FOR COUNTY CLIMATE MEASURES (FRESNO, CA)

	Temperature			Precipitation		
Independent variable	April	July	October	April	July	October
Constant	131,535	231,764	124,970	−58,846	−184,063*	16,551
Longitude	−32.8*	−59.6*	−29.2	26.7	45.2*	1.96
Latitude	−13.2	−18.2	−16.8	−19.6	21.7*	−16.33
Latitude squared	1.9×10^{-4}	2.8×10^{-4}	4.1×10^{-4}	1.6×10^{-3}	-3.1×10^{-4}	$1.6\times10^{-3*}$
Longitude squared	$2.0\times10^{-3*}$	$3.8\times10^{-3*}$	1.7×10^{-3}	-2.3×10^{-3}	$-2.7\times10^{-3*}$	-3.9×10^{-4}
Longitude × latitude	1.8×10^{-3}	2.8×10^{-3}	2.1×10^{-3}	1.5×10^{-3}	$-2.9\times10^{-3*}$	1.1×10^{-3}
Altitude	−0.56*	−1.44*	−1.00*	0.525	1.28*	1.48*
Altitude squared	$-1.6\times10^{-6*}$	$-3.0\times10^{-6*}$	$-2.3\times10^{-6*}$	$-3.7\times10^{-6*}$	$-6.5\times10^{-7*}$	$-2.4\times10^{-6*}$
Latitude × altitude	4.3×10^{-5}	8.8×10^{-5}	$7.7\times10^{-5*}$	-4.8×10^{-5}	$-1.1\times10^{-4*}$	$-1.1\times10^{-4*}$
Longitude × altitude	6.2×10^{-5}	$1.8\times10^{-4*}$	$1.1\times10^{-4*}$	-4.6×10^{-5}	$-1.5\times10^{-4*}$	$-1.7\times10^{-4*}$
Distance	−40.4*	−74.5*	−35.2	−5.47	59.4*	−26.6
Distance squared	2.6×10^{-3}	4.2×10^{-3}	2.2×10^{-3}	2.9×10^{-3}	$-4.9\times10^{-3*}$	$4.8\times10^{-3*}$
Distance × longitude	$5.2\times10^{-3*}$	$9.6\times10^{-3*}$	4.2×10^{-3}	-1.3×10^{-3}	$-6.7\times10^{-3*}$	2.6×10^{-3}
Distance × latitude	2.0×10^{-3}	3.7×10^{-3}	2.3×10^{-3}	4.3×10^{-3}	$-4.9\times10^{-3*}$	2.7×10^{-3}
Distance × altitude	6.7×10^{-5}	1.3×10^{-4}	$9.7\times10^{-5*}$	-1.9×10^{-4}	$-7.0\times10^{-5*}$	$-2.3\times10^{-4*}$
Adjusted R^2:	0.999	0.998	0.999	0.796	0.777	0.706
Standard error:	0.13	0.24	0.13	0.54	0.13	0.30
Number of observations:	331	331	331	525	525	525

Notes: Temperature is measured in Fahrenheit, and precipitation is in inches per month.
*Statistically significant at the 5-percent level.

are not in representative locations, such as the station on the top of Mt. Washington. Furthermore, some counties are large enough or contain sufficient topographical complexity that there is variation of climate within the county. We therefore proceeded by constructing an average climate for each county.

First, we assume that all the weather stations within 500 miles of the geographic center of the county provide some useful climate information. The 500-mile circle invariably draws in many stations, so that our measure does not depend too heavily on any one station.

Second, we estimate a climate surface in the vicinity of the county by running a weighted regression across all weather stations within 500 miles. The weight is the inverse of the square root of a station's distance from the county center because we recognize that closer stations contain more information about the climate of the center. We estimate a separate regression for each county since the set of stations within 500 miles and the weights (distances) are unique for each county. The dependent variables are the monthly normal temperatures and precipitation amounts for January, April, July, and October for the 30-year period. The independent variables include latitude, longitude, altitude, and distance from closest shoreline. The regression fits a second-order polynomial over these four basic variables, including interactive terms, so that there are 14 final variables in the regression, plus a constant term. Eight regressions (4 seasons × 2 measures) for each of 3,000 counties leads to over 24,000 estimated regressions.

Third, we calculate the predicted value of each climatic variable for the geographic center of the county. The predicted values of normal precipitation and temperature from the climate regressions are the independent variables for climate in the property-value regressions. This complicated interpolation procedure is intended to provide geographically accurate estimates of the climatic variables for each county.

The estimates of the climate parameters for individual counties are too numerous to present, but we show two selected counties in Tables 1 and 2. These show the indepen-

TABLE 2—INTERPOLATION FOR COUNTY CLIMATE MEASURES (DES MOINES, IOWA)

Independent variable	Temperature April	Temperature July	Temperature October	Precipitation April	Precipitation July	Precipitation October
Constant	6,425	5,006	8,967	−32,243	77,324*	41,650
Longitude	−0.919	−1.12	−2.55	7.72	−15.8*	−9.61
Latitude	−2.48	−0.829	−1.55	10.0	−32.9*	−16.32
Latitude squared	2.5×10^{-4}	2.0×10^{-5}	3.2×10^{-5}	-9.7×10^{-4}	$3.2\times10^{-3*}$	1.6×10^{-3}
Longitude squared	3.7×10^{-5}	8.1×10^{-5}	2.0×10^{-4}	-4.9×10^{-4}	6.8×10^{-4}	5.9×10^{-4}
Longitude × latitude	2.0×10^{-4}	1.0×10^{-4}	2.4×10^{-4}	-9.9×10^{-4}	$3.8\times10^{-3*}$	1.8×10^{-3}
Altitude	−0.13	0.046	0.34*	0.353	3.02*	2.09*
Altitude squared	-1.2×10^{-6}	$-1.3\times10^{-6*}$	$1.6\times10^{-6*}$	$1.1\times10^{-5*}$	-1.5×10^{-6}	$2.1\times10^{-5*}$
Latitude × altitude	2.1×10^{-5}	-1.6×10^{-5}	$-6.9\times10^{-5*}$	-1.2×10^{-4}	$-5.7\times10^{-4*}$	$-2.8\times10^{-4*}$
Longitude × altitude	1.1×10^{-5}	-9.7×10^{-6}	$-4.9\times10^{-5*}$	-3.1×10^{-5}	$-3.6\times10^{-4*}$	$-3.2\times10^{-4*}$
Distance	1.14	−1.17	−0.564	−0.150	26.8	18.6
Distance squared	1.8×10^{-4}	-3.1×10^{-4}	-1.9×10^{-4}	5.8×10^{-4}	-1.2×10^{-3}	1.4×10^{-3}
Distance × longitude	-4.4×10^{-5}	1.9×10^{-4}	-1.2×10^{-4}	-4.1×10^{-4}	-2.7×10^{-3}	-1.9×10^{-3}
Distance × latitude	-3.6×10^{-4}	2.2×10^{-4}	9.0×10^{-5}	4.2×10^{-4}	$-5.4\times10^{-3*}$	-3.8×10^{-3}
Distance × altitude	-2.2×10^{-5}	3.2×10^{-5}	$9.9\times10^{-5*}$	-1.7×10^{-4}	$6.9\times10^{-4*}$	$3.6\times10^{-4*}$
Adjusted R^2:	0.999	0.999	0.999	0.989	0.987	0.976
Standard error:	0.04	0.04	0.04	0.14	0.17	0.15
Number of observations:	928	928	928	1,477	1,477	1,477

Notes: Temperature is measured in Fahrenheit, and precipitation is in inches per month.
*Statistically significant at the 5-percent level.

dent variables as well as the coefficients and summary regression statistics for Fresno, California, and Des Moines, Iowa. Note that more coefficients are significant in the Fresno regressions than in the Des Moines regressions. There is more variation across the sample in Fresno because of the effects of the coast and nearby mountain ranges. Although there are more significant coefficients in the California regression, the Iowa regression has a better overall fit and smaller standard errors. In general, the fit east of 100 degrees longitude (the east slope of the Rocky Mountains) was tighter than in the West.

In order to gain some sense of the reliability of this geographic approximation method, we predicted the climate for each of the weather stations. Dropping the weather station itself, we predicted the climatic variables for the station from all stations within 500 miles in the manner explained above. Comparing these results with the actual measurements from each station reveals that the approximation method predicts between 87 percent and 97 percent of the variation in precipitation in the continental United States and between 97 percent and 99 percent of the variation in temperature. It should be noted that, even in a statistically stationary environment, the observations of "climate" themselves contain error because they contain only 30 observations. Depending upon the relative importance of idiosyncratic error in climate versus misspecification error in our equation, the predictions might actually be superior to the recorded observations themselves. In any case, the predictions serve as sophisticated interpolations of the climate between stations.

II. Empirical Analysis

The Ricardian approach estimates the importance of climate and other variables on farmland values. As noted above, land values are the expected present value of future rents. There is little reason for the riskless interest rate to vary across counties in the United States, but the risk and capital-gains components of land value might vary considerably. For example, California agricultural land near growing cities might well have a larger capital-gains component than would rural land in an economically stagnant coal-mining region of Appalachia. Moreover, there are major potential errors in measurement of land values since values are estimated by farmers, and such estimates are often unreliable. However, there is no reason to believe that the errors of measurement are correlated with independent data such as temperature or precipitation. The major effect of measurement errors will be imprecision of the econometric estimates rather than bias in the estimation of the coefficients or in the estimate of the economic value of climate on agriculture.

We regress land values on climate, soil, and socioeconomic variables to estimate the best-value function across different counties. There are 2,933 cross-sectional observations. The means have been removed from the independent variables in this regression. The quadratic climate variables are consequently easier to interpret. The linear term reflects the marginal value of climate evaluated at the U.S. mean, while the quadratic term shows how that marginal effect will change as one moves away from the mean.

We present several regressions in Table 3. In order to give a sense of the importance of the nonfarm variables in the model, we begin with a model that contains only climate variables. The first set of regressions in Table 3 is a quadratic model that includes the eight measures of climate (four months of precipitation and temperature). For each variable, linear and quadratic terms are included to reflect the nonlinearities that are apparent from field studies.

In the remainder of regressions, we include urban, soil, and other environmental variables to control for extraneous factors influencing land values and farm revenues. This raises the question of how the counties should be weighted. A first set of regressions uses the *cropland weights*, in which observations are weighted by the percentage of each county in cropland. Counties with a large fraction of cropland should provide a better reading on price determination because other influences, such as cities or forests, are minimized; these results are particularly useful for the grain belt. A second set of regressions uses *crop-revenue weights*; that is, observations are weighted by the aggregate value of crop revenue in each county. This second weighting scheme emphasizes those counties that are most important to total agricultural production, even though some of the counties might have their land values affected by large neighboring cities; it also places greater weight on counties where more valuable crops are grown. On the whole, the cropland measure tends to emphasize the corn, wheat, and soybean belt and therefore reflects the influence of climate on the grains. The crop-revenue weights, by contrast, give more influence to the truck farms and citrus belt of the coast lands, and the crop-revenue regressions thus reflect a broader definition of agriculture.

The results of this analysis are shown in columns (ii)–(v) of Table 3. The squared terms for most of the climate variables are significant, implying that the observed relationships are nonlinear. However, some of the squared terms are positive, especially for precipitation, implying that there is a minimally productive level of precipitation and that either more or less precipitation will increase land values. The negative quadratic coefficient implies that there is an optimal level of a climatic variable from which the value function decreases in both directions.

The overall impact of climate as measured by the marginal impacts is largely the same across the different models, although the quantitative estimates vary. All models suggest that higher winter and summer temperatures are harmful for crops; that higher fall temperatures and higher winter and spring rainfall are beneficial for crops; but that higher summer or fall rainfall is harmful. The two weighting schemes differ, however, in terms of their assessment of the relative importance of winter versus summer temperature. The cropland model finds higher winter temperatures less harmful, valuing a 1°F increase by between \$89 and \$103 per acre, whereas the crop-revenue model finds this effect more harmful, with estimated impacts between \$138 and \$160

TABLE 3—REGRESSION MODELS EXPLAINING FARM VALUES

	Cropland weights			Crop-revenue weights	
Independent variables	1982 (i)	1982 (ii)	1978 (iii)	1982 (iv)	1978 (v)
Constant	1,490	1,329	1,173	1,451	1,307
	(71.20)	(60.18)	(57.95)	(46.36)	(52.82)
January temperature	−57.0	−88.6	−103	−160	−138
	(6.22)	(9.94)	(12.55)	(12.97)	(13.83)
January temperature squared	−0.33	−1.34	−2.11	−2.68	−3.00
	(1.43)	(6.39)	(11.03)	(9.86)	(14.11)
April temperature	−137	−18.0	23.6	13.6	31.8
	(10.81)	(1.56)	(2.23)	(1.00)	(2.92)
April temperature squared	−7.32	−4.90	−4.31	−6.69	−6.63
	(9.42)	(7.43)	(7.11)	(9.44)	(11.59)
July temperature	−167	−155	−177	−87.7	−132
	(13.10)	(14.50)	(18.07)	(6.80)	(12.55)
July temperature squared	−3.81	−2.95	−3.87	−0.30	−1.27
	(5.08)	(4.68)	(6.69)	(0.53)	(2.82)
October temperature	351.9	192	175	217	198
	(19.37)	(11.08)	(11.01)	(8.89)	(9.94)
October temperature squared	6.91	6.62	7.65	12.4	12.4
	(6.38)	(7.09)	(8.93)	(12.50)	(15.92)
January rain	75.1	85.0	56.5	280	172
	(3.28)	(3.88)	(2.81)	(9.59)	(7.31)
January rain squared	−5.66	2.73	2.20	−10.8	−4.09
	(1.86)	(0.95)	(0.82)	(3.64)	(1.72)
April rain	110	104	128	82.8	113
	(4.03)	(4.44)	(5.91)	(2.34)	(4.05)
April rain squared	−10.8	−16.5	−10.8	−62.1	−30.6
	(1.17)	(1.96)	(1.41)	(5.52)	(3.35)
July rain	−25.6	−34.5	−11.3	−116	−5.28
	(1.87)	(2.63)	(0.94)	(6.06)	(0.34)
July rain squared	19.5	52.0	37.8	57.0	34.8
	(3.42)	(9.43)	(7.54)	(8.20)	(6.08)
October rain	−2.30	−50.3	−91.6	−124	−135
	(0.09)	(2.25)	(4.45)	(3.80)	(5.15)
October rain squared	−39.9	2.28	0.25	171	106
	(2.65)	(0.17)	(0.02)	(14.17)	(11.25)
Income per capita		71.0	65.3	48.5	47.1
		(15.25)	(15.30)	(6.36)	(7.39)
Density		1.30	1.05	1.53	1.17
		(18.51)	(16.03)	(18.14)	(17.66)
Density squared		-1.72×10^{-4}	-9.33×10^{-5}	-2.04×10^{-4}	-9.38×10^{-5}
		(5.31)	(3.22)	(7.47)	(4.57)
Latitude		−90.5	−94.4	−105	−85.8
		(6.12)	(6.95)	(5.43)	(5.33)
Altitude		−0.167	−0.161	−0.163	−0.149
		(6.09)	(6.41)	(4.72)	(5.20)
Salinity		−684	−416	−582	−153
		(3.34)	(2.20)	(2.59)	(0.81)
Flood-prone		−163	−309	−663	−740
		(3.34)	(6.98)	(8.59)	(11.99)
Wetland		−58.2	−57.5	762	230
		(0.47)	(0.51)	(4.41)	(1.72)
Soil erosion		−1,258	−1,513	−2,690	−2,944
		(6.20)	(8.14)	(8.21)	(11.23)
Slope length		17.3	13.7	54.0	30.9
		(2.91)	(2.49)	(6.24)	(4.54)
Sand		−139	−35.9	−288	−213
		(2.72)	(0.77)	(4.16)	(3.95)
Clay		86.2	67.3	−7.90	−18.0
		(4.08)	(3.47)	(0.22)	(0.63)
Moisture capacity		0.377	0.510	0.206	0.450
		(9.69)	(14.21)	(3.82)	(10.07)
Permeability		−0.002	−0.005	−0.013	−0.017
		(1.06)	(2.53)	(5.58)	(8.61)
Adjusted R^2:	0.671	0.782	0.784	0.836	0.835
Number of observations:	2,938	2,938	2,941	2,941	2,941

Notes: The dependent variable is the value of land and buildings per acre. All regressions are weighted. Values in parenthesis are t statistics.

per acre. However, a 1°F increase in summer temperature decreases farm values by only \$88–\$132 according to the crop-revenue model but by between \$155 and \$177 in the cropland model. Except for spring rains, the crop-revenue model suggests that rain has a much larger effect on land value than the cropland model. For example, the crop-revenue model suggests that winter rain increases farm values between \$172 and \$280 per monthly inch, whereas the cropland model suggests an effect between \$57 and \$85 per monthly inch.

The predicted overall effects from the existing climate across the United States are shown in Figures 2 and 3. These maps show the *Ricardian values of climate* by county in 1982, that is, the partial effect of climate on property values. To construct each map, we begin with the difference between the estimated climate for each county and the national average climate. We then multiply these differences by the estimated coefficients in Table 3 and sum them across the climate variables. Figures 2 and 3 show the estimated contribution of climate to the farmland value in each county. The results match folk wisdom about farm values (for example, the infamous 100th meridian of American history can be seen sharply in Figure 2). The most valuable climates are along the west coast, the corn belt near Chicago, and the northeast. The least valuable areas are the southwest and southeast regions. Both figures show almost identical geographic patterns, indicating that the results are stable; similar results were also found using 1978 data.

The control variables in Table 3 provide a rich set of results in and of themselves. Economic and soil variables play a role in determining the value of farms. Farm values are higher in denser, growing, and wealthier counties because of higher local demand for food and the potential for conversion of land to nonfarm uses. Farm values respond as expected to other environmental factors such as solar flux (latitude) and altitude. Salinity, likelihood of flooding, presence of wetlands, and soil erosion all act negatively as expected. Slope length was slightly beneficial to land values. Irrigation is left out of the regressions shown in Table 3 because irrigation is clearly an endogenous reaction to climate. However, when included, irrigation is a strongly positive variable, increasing land values substantially; which is not surprising, given the crucial importance of irrigation in many areas of the arid West.[6]

One hypothesis suggested in the theory section is that the impacts of environmental effects would be exaggerated by a gross-revenue model. We explore this hypothesis in Table 4 by regressing the same climate and contol variables on the gross revenue earned from crops. The marginal effects in Table 4 for the farm-revenue model suggest similar seasonal patterns as the farm-value equation with the exception of spring. Warmer Aprils reduce farm revenues, whereas they increase farm values. Wetter springs, good for farm values, reduce farm revenues according to the cropland model but increase farm revenues according to the crop-revenue model.

The magnitude of damages predicted by the gross-revenue model, however, are generally larger than the effects predicted by the Ricardian model. To compare the two approaches, we need to translate the annual rents into land value using the discount rate defined in Section II. Based on asset returns and farm earnings, a real discount rate of 5 percent per annum appears most suitable.[7] At this discount rate, the marginal coefficients in Table 4 should be multiplied

[6]Including irrigation does not significantly change the results of the paper.

[7]According to Roger Ibbotson and Gary Brinson (1987), farmland prices over the period 1947–1984 had a compound annual return (income and capital gains) of 9.6 percent while the GNP deflator rose at an average of 4.4 percent annually. This produces an average real yield of 4.99 percent per annum. By comparison, all real-estate investments had an average real yield of 4.4 percent per annum over this period. Another comparison is the rate of profit on farms, defined as the net income of farms divided by total value of farms and farmland. For the three census years of 1974, 1978, and 1982, the average rate of profit on farms was 5.02 percent per annum.

TABLE 4—REGRESSION MODELS EXPLAINING FARM REVENUES

	Cropland weights		Crop-revenue weights	
Independent variables	1982 (i)	1978 (ii)	1982 (iii)	1978 (iv)
Constant	180	143	213	186
	(31.37)	(28.09)	(16.61)	(16.27)
January temperature	−11.6	−6.65	16.1	16.4
	(5.00)	(3.21)	(3.19)	(3.55)
January temperature squared	−0.048	0.006	0.867	0.659
	(0.88)	(0.13)	(7.80)	(6.71)
April temperature	−23.5	−20.3	−47.7	−39.3
	(7.89)	(7.63)	(8.62)	(7.83)
April temperature squared	−1.31	−1.12	−2.74	−2.26
	(7.67)	(7.43)	(9.43)	(8.55)
July temperature	−27.2	−21.5	−10.0	−7.20
	(9.85)	(8.66)	(1.90)	(1.49)
July temperature squared	0.053	−0.166	1.27	0.341
	(0.32)	(1.14)	(5.52)	(1.65)
October temperature	51.3	41.4	−2.12	2.92
	(11.43)	(10.43)	(0.21)	(0.32)
October temperature squared	0.637	0.598	−0.025	0.569
	(2.62)	(2.85)	(0.06)	(1.58)
January rain	30.1	21.4	−28.9	−11.5
	(5.29)	(4.26)	(2.42)	(1.06)
January rain squared	−4.10	−2.93	−4.08	−3.33
	(5.49)	(4.49)	(3.36)	(3.04)
April rain	−22.5	−23.2	47.5	16.0
	(3.67)	(4.29)	(3.28)	(1.24)
April rain squared	−2.46	4.65	−5.73	2.65
	(1.12)	(2.39)	(1.24)	(0.63)
July rain	−3.29	2.12	−64.5	−33.3
	(0.97)	(0.70)	(8.25)	(4.61)
July rain squared	10.8	6.74	22.8	13.2
	(6.93)	(5.23)	(8.03)	(5.02)
October rain	−40.2	−16.1	−44.4	−16.3
	(6.93)	(3.17)	(3.32)	(1.35)
October rain squared	27.2	17.4	33.8	9.32
	(7.73)	(5.62)	(6.84)	(2.15)
Income per capita	0.568	0.803	3.37	8.24
	(0.47)	(0.73)	(1.08)	(2.81)
Density	0.172	0.133	0.457	0.280
	(9.46)	(8.47)	(13.28)	(9.14)
Density squared	2.86×10^{-6}	2.92×10^{-6}	-4.47×10^{-5}	-1.92×10^{-5}
	(0.34)	(0.43)	(3.99)	(2.03)
Latitude	−24.3	−15.4	−72.6	−41.6
	(6.28)	(4.44)	(9.15)	(5.59)
Altitude	−0.049	−0.033	−0.096	−0.059
	(6.91)	(5.03)	(6.78)	(4.47)
Salinity	−156	−149	−502	−427
	(2.97)	(3.23)	(5.44)	(4.90)
Flood-prone	29.8	25.4	−40.7	−1.45
	(2.36)	(2.27)	(1.29)	(0.05)
Wetland	70.9	64.8	234	115
	(2.21)	(2.32)	(3.31)	(1.86)
Soil erosion	−169	−74.5	−413	−360
	(3.18)	(1.60)	(3.08)	(2.98)
Slope length	−1.18	−1.21	−15.3	−13.5
	(0.73)	(0.85)	(4.33)	(4.31)
Sand	28.7	32.3	70.3	46.7
	(2.18)	(2.84)	(2.49)	(1.88)
Clay	11.1	12.3	−48.1	−31.8
	(1.99)	(2.49)	(3.32)	(2.43)
Moisture capacity	0.062	0.050	0.101	0.058
	(6.10)	(5.49)	(4.57)	(2.79)
Permeability	0.001	0.001	−0.001	−0.005
	(2.22)	(2.15)	(6.94)	(5.30)
Adjusted R^2:	0.525	0.509	0.800	0.762
Number of observations:	2,834	2,443	2,834	2,443

Notes: The dependent variable is the gross value of crop revenue per acre per year. All regressions are weighted. Values in parenthesis are t statistics.

TABLE 5—PREDICTED IMPACT OF GLOBAL WARMING ON FARMLAND VALUES AND FARM RENTS

		Change in farmland values (billions of dollars, 1982 prices)		Change in farmland rents (percentage of 1982 farm marketings)	
Year	Weight	Impact	Truncated impact	Impact	Truncated impact
1982	Cropland	−$125.2	−$118.8	−4.4	−4.2
1978	Cropland	−$162.8	−$141.4	−5.7	−4.9
1982	Crop revenue	$34.5	$34.8	1.2	1.2
1978	Crop revenue	−$14.0	$21.0	−0.5	0.7

Notes: The global-warming scenario is a uniform 5°F increase with a uniform 8-percent precipitation increase. The "impact" column shows the estimated loss; the "truncated impact" columns show the impact when the loss in farmland value in each county is limited to the original value of the land. The last two columns are annualized impacts, as explained in the text, as a percentage of 1982 farm marketings.

by 20 to make them comparable with the present-value estimates in Table 3. Making this adjustment, a 1°F increase in summer temperature decreases the present value of farms by between $140 and $540 according to the gross-revenue model but only between $88 and $177 according to the Ricardian models.

One concern with the Ricardian approach to climate effects is that the results may not be robust over time and that the weather and economic factors in a given year may have distorted the results. We consequently estimated the model again using data from 1978. These values have been converted to 1982 dollars using the GNP deflator obtained from the *1991 Economic Report of the President.* The 1978 results are surprisingly similar to the findings using the 1982 data. The control variables have similar impacts in both years. Evaluating the marginal effects of climate in 1978 at the national mean and comparing the results with 1982 shows that the climatic variables are also similar in 1978 and 1982 with few exceptions. The pattern of climate effects on agriculture is stable over time, but apparently some factors can alter the magnitude of the effects from year to year.

III. Implications for Greenhouse Warming

The Ricardian analysis in the previous section shows that climate has complicated effects on agriculture, highly nonlinear and varying by season. An important application of this analysis is to project the impact of global warming on American agriculture. For this projection, we take a conventional CO_2 doubling scenario, which is associated with a 5°F increase in global mean surface temperature (see Intergovernmental Panel on Climate Change, 1990; National Academy of Sciences Panel on Greenhouse Warming, 1992). According to most projections, such an increase will occur sometime in the second half of the next century if current trends continue. According to the survey by the Intergovernmental Panel on Climate Change, a 5°F temperature increase will be accompanied by an 8-percent average increase in precipitation. These changes are applied uniformly by season and region to the United States in the calculations that follow. In principle, they show the impact of climate change including all adaptations, although they omit the impact of CO_2 fertilization and price effects.

Table 5 shows the results of this experiment for the two years and sets of weights. The "impact" columns show the estimated impact of global warming on farmland values; the "truncated impact" columns truncate these losses if they drive land values below zero. This truncated impact is the preferred economic measure. The estimates diverge dramatically depending upon whether cropland or crop revenues are used for weighting. Under the cropland weights, the loss in land value from warming ranges from \$119 billion to \$141 billion; assuming that the annual crop loss is 5 percent of this value,[8] the annual loss ranges from \$6 billion to \$8 billion (in 1982 prices at 1978 or 1982 levels of output). Relating this value to gross farm income in 1982 of \$164 billion, the annual damage is in the neighborhood of 4–5 percent. The cropland model emphasizes the unattractiveness of a warmer climate for an agriculture that emphasizes grains, which have relatively low value per acre and thrive in the relatively cool climate of the northern United States.

Strikingly different results emerge if we use the crop-revenue approach. For these, the net impact of warming (again without CO_2 fertilization) is slightly positive, suggesting an increase of \$20–\$35 billion in farmland values. Annualizing these capital values, this suggests a gain of between \$1 billion and \$2 billion per year. As a fraction of 1982 revenue, this amounts to about a 1-percent gain. The differing results arise because the crop-revenue approach weights relatively more heavily the irrigated lands of the West and South that thrive in a Mediterranean and subtropical climate, a climate that will become relatively more abundant with a warming. Including this broader set of crops and adaptations paints a more optimistic picture because the gains from the sunbelt crops tend to offset the losses in the marginal grain regions.

The striking difference between the crop-revenue and cropland approaches is a useful reminder of how we can be misled by our mental images. The specter of global warming calls up the vista of corn blistering on the stalk or desiccated wheat fields. Yet the major grains so vulnerable to drought—wheat and corn—represented only \$22.5 billion of the \$143 billion of farm marketings in 1982. Our results suggest that the vulnerability of American agriculture to climate change may be exaggerated if the analysis is limited to the major grains. A broader vision should also include the warm-weather crops such as cotton, fruits, vegetables, rice, hay, and grapes in addition to other sectors such as livestock and poultry. Whereas past production-function studies focus ominously on the vulnerable cool-weather grains, the comprehensive crop-revenue Ricardian model reminds us that the irrigated warm-weather crops may be a silver lining behind the climate-change cloud.

Figures 4 and 5 provide geographic detail for these global-warming scenarios. According to the cropland model shown in Figure 4, warming will be particularly harmful for the entire southern part of the United States and will only be beneficial to the northern fringe of the country. The crop-revenue model of Figure 5 suggests, by contrast, that global warming will be beneficial to California and the citrus belt of the Southeast as well as the corn and wheat belts of the Midwest. Global warming will be harmful, in this model, only to the relatively unimportant mountainous regions of Appalachia and the Rocky Mountains.

It will be useful to compare these estimates with results from other studies. In its analysis, Smith and Tirpak (1989) surveyed a number of different climate and agriculture models to estimate the impact of CO_2 doubling. Omitting CO_2 fertilization, the EPA concluded that the impact would lie in the range of \$6 billion to \$34 billion per year (in 1982 prices). Cline (1992) used two different approaches, the EPA estimate and a modification of Rind et al. (1990), both of which project losses of \$20 billion per year without CO_2 fertilization. It is instructive to note that these studies all rely on the production-function approach and apply it to grains; these estimates therefore are closest to our cropland model, and as was predicted in the theoretical section above, they show a higher estimate of damage for that universe than the Ricardian approach—approximately triple the estimates in Table 5. By excluding the nongrain, warm-weather crops, these studies further bias upward the estimates of damage, as is shown by the

[8]See the discussion of this issue in the last section and in footnote 6.

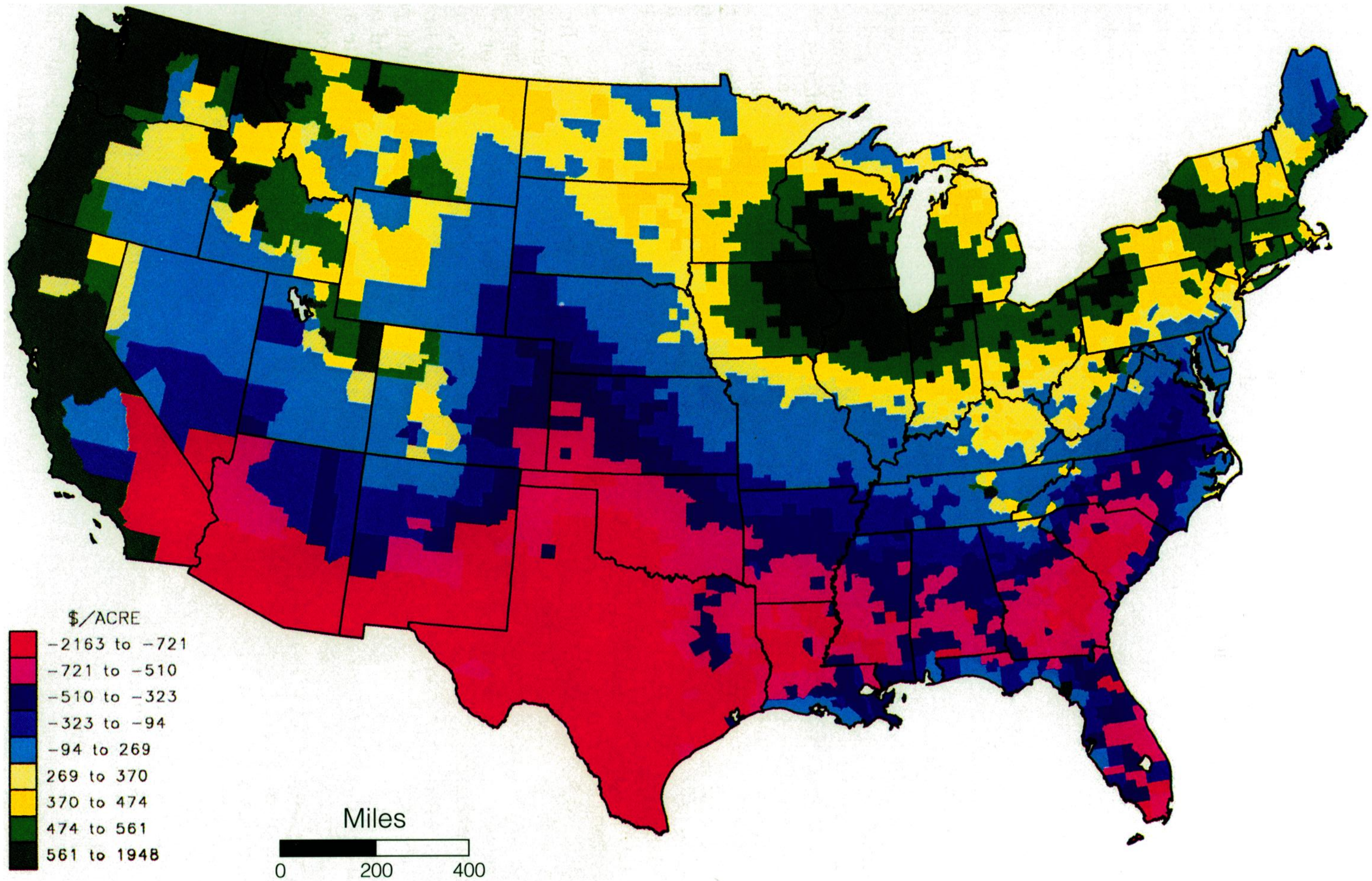

FIGURE 2. INFLUENCE OF CURRENT CLIMATE ON FARM VALUES: CROPLAND WEIGHTS
Note: Farm value is measured as the difference in dollars per acre from the sample average, 1982 prices.

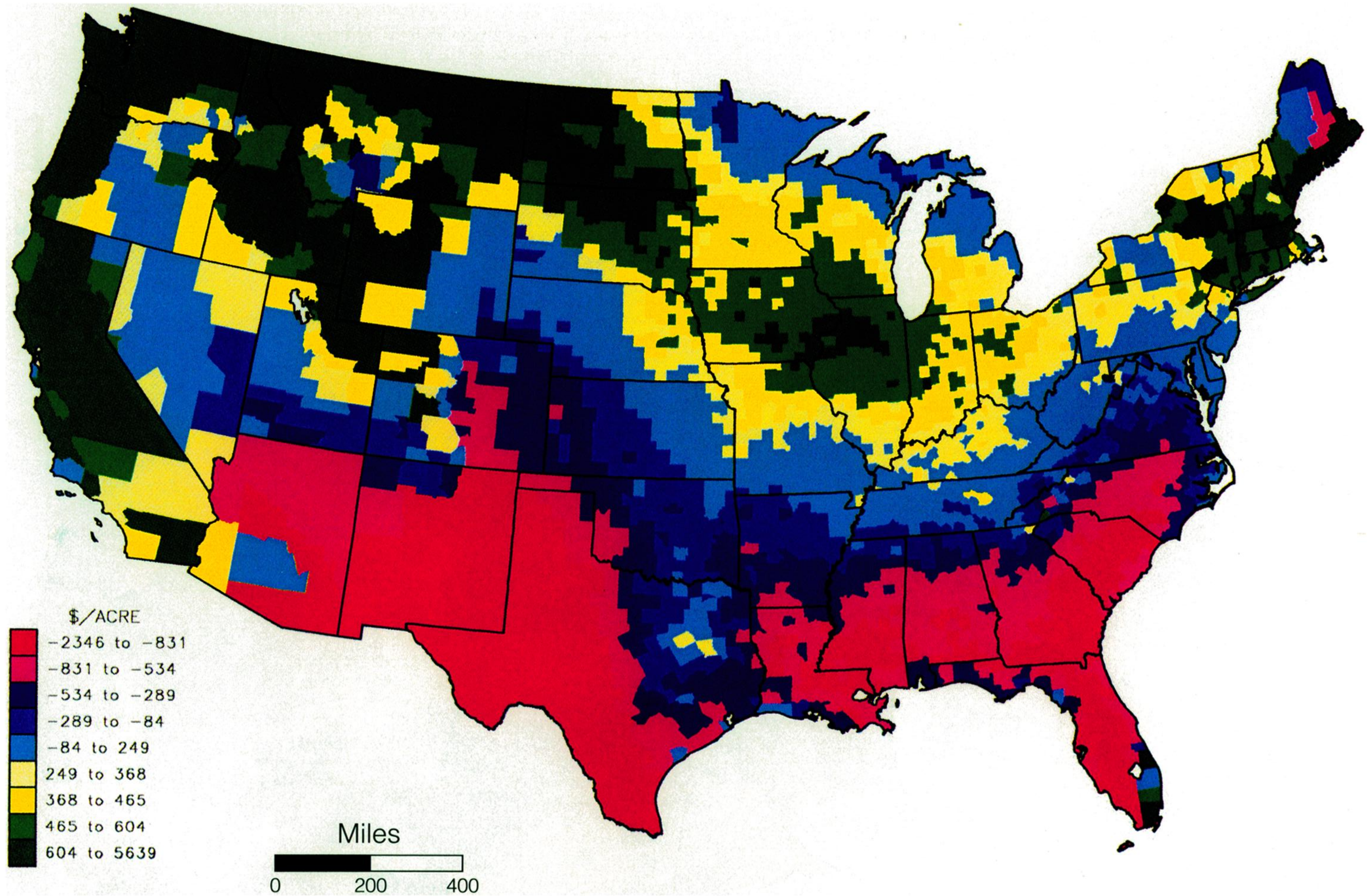

FIGURE 3. INFLUENCE OF CURRENT CLIMATE ON FARM VALUES: CROP-REVENUE WEIGHTS
Note: Farm value is measured as the difference in dollars per acre from the sample average, 1982 prices.

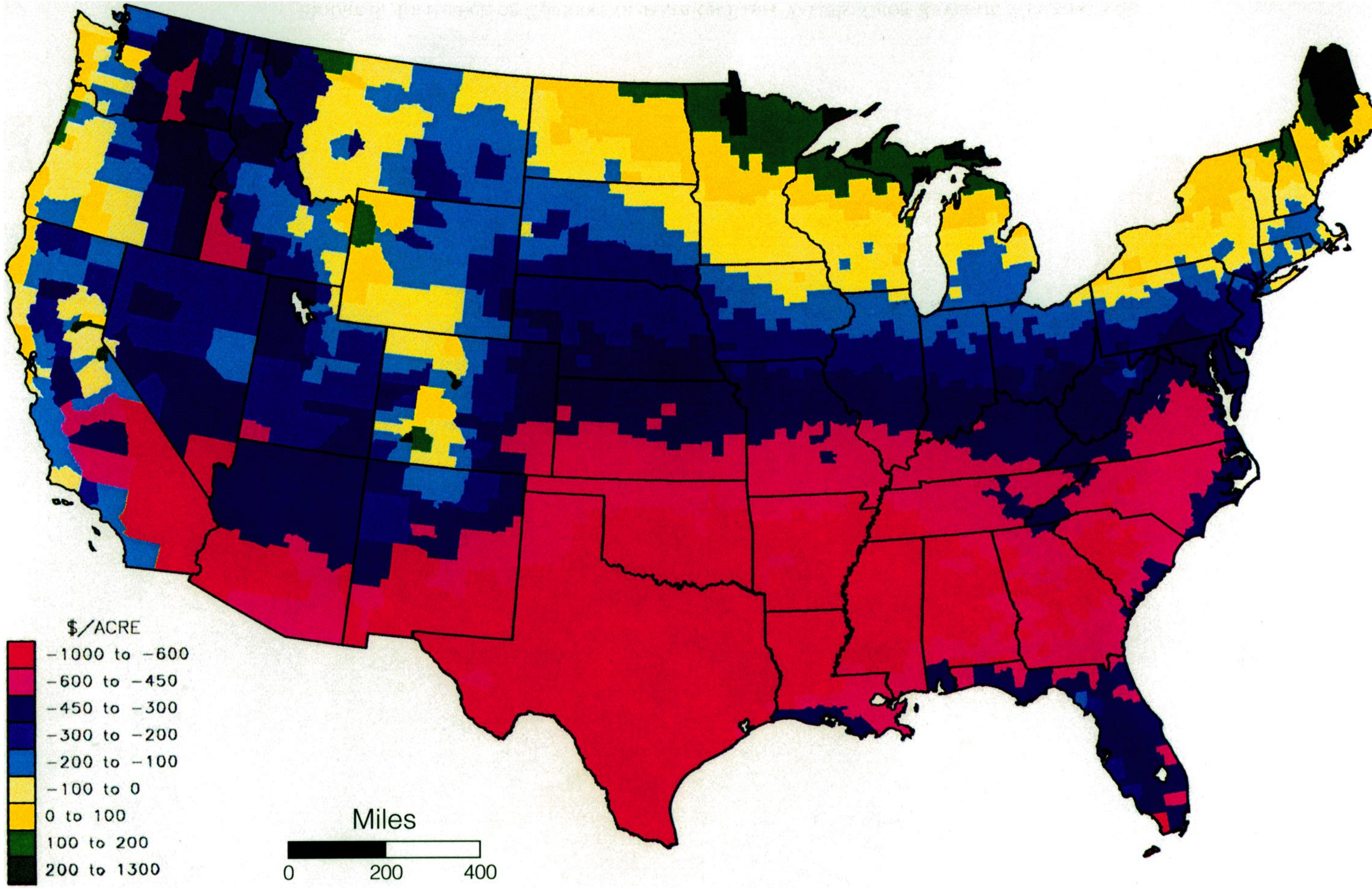

FIGURE 4. CHANGE IN FARM VALUE FROM GLOBAL WARMING: CROPLAND WEIGHTS
Note: The map shows the change in terms of dollars per acre for a 5°F uniform warming and an 8-percent increase in precipitation, 1982 prices.

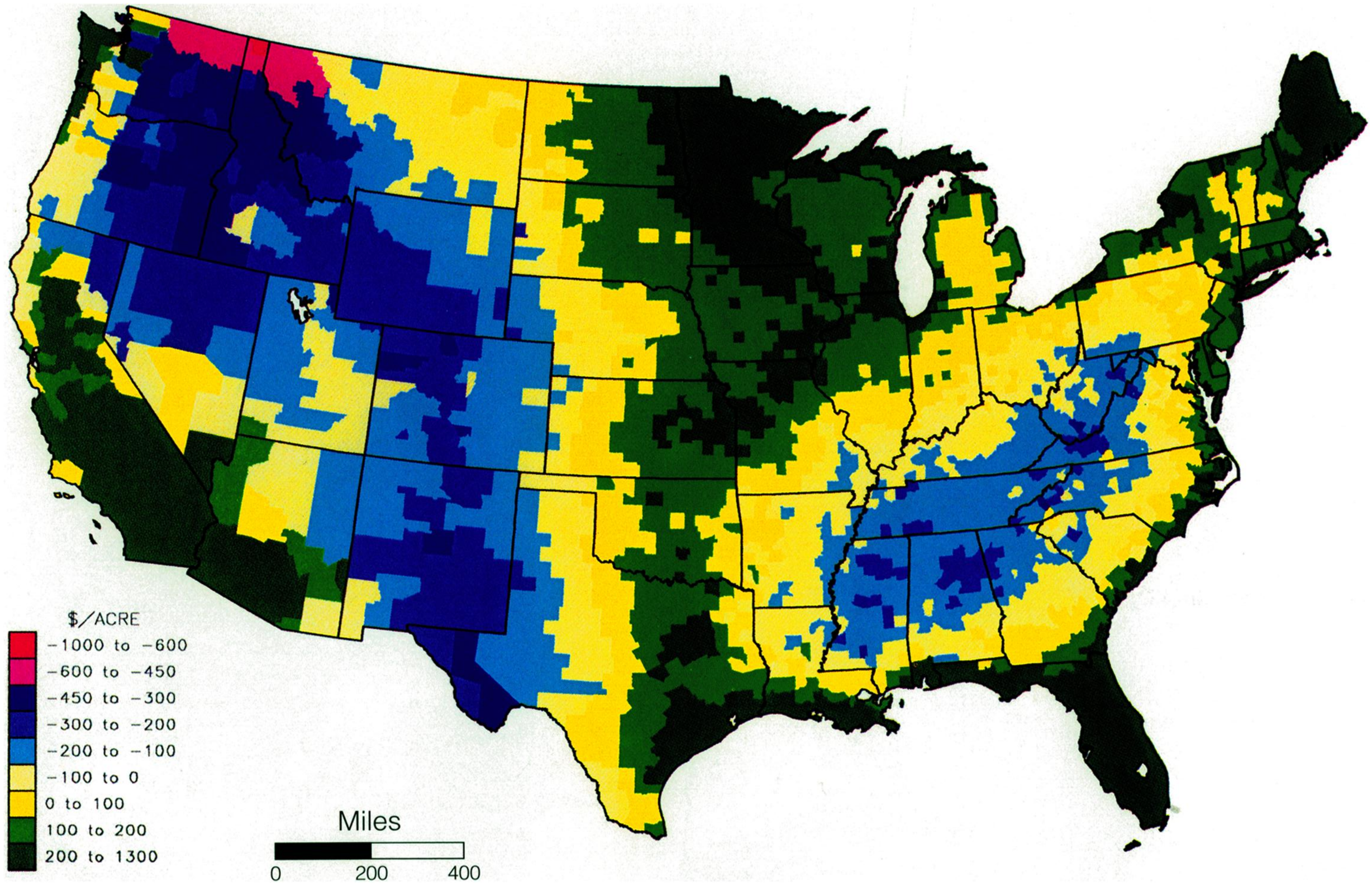

FIGURE 5. CHANGE IN FARM VALUE FROM GLOBAL WARMING: CROP-REVENUE WEIGHTS

Notes: The map shows the change in terms of dollars per acre for a 5° F uniform warming and an 8-percent increase in precipitation, 1982 prices.

comparison between the cropland and the crop-revenue models.

The results in Table 5 are based on a highly stylized global-warming scenario and are therefore quite tentative. In research underway, we are drawing estimated global-warming results from large-scale general circulation models; these should allow differentiation among broad regions of the United States. In addition, the effects of CO_2 fertilization should be included, for some studies indicate that this may produce a significant increase in yields. Other omitted variables are the effect of extremes and ranges in climatic variables as well as the effect of changes in irrigation. Notwithstanding these omissions, the present paper does provide a benchmark for projecting the impact of global warming on American agriculture. Using the narrow definition of crops, the negative impact is estimated to lie between 4 percent and 6 percent of the value of farm ouput. Using a more inclusive definition that weights warm-weather crops and irrigated agriculture more heavily, our projections suggest that global warming may be slightly beneficial to American agriculture.

Appendix A: Definitions of Major Variables Used in this Study

Constant: a term equal to 1
January temperature: normal daily mean temperature (°F) from 1951 to 1980 in the month of January
January temperature squared: value of January temperature squared
April temperature: normal daily mean temperature (°F) from 1951 to 1980 in the month of April
April temperature squared: value of April temperature squared
July temperature: normal daily mean temperature (°F) from 1951 to 1980 in the month of July
July temperature squared: value of July temperature squared
October temperature: normal daily mean temperature (°F) from 1951 to 1980 in the month of October
October temperature squared: value of October temperature squared
January rain: normal precipitation (inches) from 1951 to 1980 in the month of January
January rain squared: value of January rain squared
April rain: normal precipitation (inches) from 1951 to 1980 in the month of April
April rain squared: value of April rain squared
July rain: normal precipitation (inches) from 1951 to 1980 in the month of July
July rain squared: value of July rain squared
October rain: normal precipitation (inches) from 1951 to 1980 in the month of October
October rain squared: value of October rain squared
Income per capita: annual personal income per person in the county, 1984
Density: resident population per square mile, 1980
Density squared: value of density squared
Latitude: latitude measured in degrees from southernmost point in United States
Altitude: height from sea level (feet)
Migration: net of incoming people minus outgoing people from 1980 to 1986 for the county
Salinity: percentage of land that needs special treatment because of salt/alkaline minerals in the soils
Flood prone: percentage of land that is prone to flooding
Irrigated: percentage of land where irrigation provides at least 50% of water needs
Wetland: percentage of land considered wetland
Soil erosion: K-factor soil (erodibility factor) in hundredths of inches
Slope length: length of slope (feet) (not steepness)
Wind erosion: measure of wind erosion (hundredths of inches)
Farm value: estimate of the current market value of farmland including buildings expressed in dollars per acre, 1982
Farm revenue: gross revenue from crops sold in 1982 in dollars per acre
Sdist: linear distance from the nearest shoreline

Long: longitude measured in degrees from the easternmost point of the United States
Permeability: soil permeability (inches per hour)
Moisture capacity: available water capacity (inches/pound)

APPENDIX B: DATA ON FARMS AND VALUE OF LAND AND BUILDINGS[9]

The data on farms and on farmland values are central to this study. This appendix describes the definition and sources of the data. The current definition of a farm, first used for the *1974 Census of Agriculture* final reports, is any place from which $1,000 or more of agricultural products were sold or normally would have been sold during the census year. Land in farms is an operating-unit concept and includes land owned and operated as well as land rented from others. The acreage designated as "land in farms" consists primarily of agricultural land used for crops, pasture, or grazing. It also includes woodland and wasteland not actually under cultivation or used for pasture or grazing, provided it was part of the farm operator's total operation.

The land is defined to lie in the operator's principal county, that is, the county where the largest value of agricultural products was raised or produced. Irrigated land includes land watered by any artificial or controlled means, such as sprinklers, furrows or ditches, and spreader dikes. Cropland includes land from which crops were harvested or hay was cut, land in orchards, citrus groves, vineyards, nurseries, and greenhouses, land used only for pasture or grazing that could have been used for crops without additional improvement, and all land planted in crops that were grazed before the crops reached maturity. Also included were all cropland used for rotation pasture and lands in government diversion programs that were pastured.

[9]This description is drawn from the *City and County Data Book*, and the underlying data are from *1982 Census of Agriculture* (U.S. Bureau of the Census, 1984).

Respondents were asked to report their estimate of the current market value of land and buildings owned, rented, or leased from others, and of land rented or leased to others. Market value refers to the respondent's estimate of what the land and buildings would sell for under current market conditions. If the value of land and buildings was not reported, it was estimated during processing by using the average value of land and buildings from a similar farm in the same geographic area.

The value of products sold by farms represents the gross market value before taxes and production expenses of all agricultural products sold or removed from the place regardless of who received the payment. In addition, it includes the loan value received in 1982 for placing commodities in the Commodity Credit Corporation loan program.

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