A County-Level Approach to Regional Resource Analysis Based on Climate Simulation*

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ABSTRACT

This paper describes the use of a county-level approximation of the grid cells of a general circulation model as an approach to using environmental and resource data in analyzing the effects of climate change. As a demonstration, the effects are estimated of a possible climate change due to a doubling of atmospheric CO_2 on the production of soybeans using two simple approaches based on grid cell averages of county-level yield data. With the first approach, we assume that the future yields will be determined by current climate–yield relationships. The actual 1978 climate (approximate growing-degree days and precipitation in the growing season) corresponding to 1978 yield levels is calculated. The climate characteristics of grid cells with major (grid cell-averaged yield of 56.9–299.3 kg/ha) and minor (1.6–11.6 kg/ha) soybean yield are estimated. Potential future major and minor yields are then estimated from a simulated changed climate. With the second approach, future yields are estimated using a multiple regression equation that relates yield to simulated June and August temperature and July, August, and September–June precipitation. These two simple analyses, which ignore many important factors such as soil fertility, technological advances, development of new soybean varieties, and the validity of the climate simulations, show that soybean yields might decline in the areas where the crop is now grown, but that soybean agriculture could expand northwards and eastwards if other factors permit. These analyses confirm that it is possible to perform analyses of the effects of climate change using county-level data, although such analyses would have to consider additional factors before the results themselves would be credible.

1. Introduction

Recently there has been growing interest if—and how—predicted climatic changes (especially from increased atmospheric concentrations of CO_2 and other radiatively active gases) could affect agriculture, water supplies, forests, ecosystems, and human health (e.g., Gates 1985; Rosenzweig 1985; White 1985; Cohen 1986; Solomon 1986). Atmospheric general circulation models (GCMs) are among the predictive tools used to simulate possible future climates; they model important physical processes that determine climate, incorporating approximations of actual geography and topography.

One GCM that has been widely used in climate studies is the model II GCM of the Goddard Institute for Space Studies (GISS) (Hansen et al. 1983). The GISS model predicts temperature and precipitation (among other variables) globally for 8° × 10° grid cells, and has been used to simulate both current and doubled-CO_2 climates (Hansen et al. 1984). Cohen (1986) studied the effects of a CO_2-induced climate change, as projected by both the GISS GCM and the GCM of the Geophysical Fluid Dynamics Laboratory (GFDL), on water supply in the Great Lakes Basin. Rosenzweig (1985) examined the potential effects of a CO_2-induced climate change, as projected by the GISS GCM, on the distribution of major wheat types in North America.

Gates (1985) noted that much progress is needed before GCM output can be used to analyze the effects of climate change. In particular, there are two principal geographical obstacles to the analysis of climate effects on a particular resource. First, while gradients and events in actual weather and climate can occur on a scale of meters or kilometers (Clark 1985), the horizontal resolution of GCMs is on the order of hundreds of kilometers. Second, the geographical scale of the distribution of resources (e.g., soil types, plant communities, and watersheds) is poorly accommodated by the horizontal resolution of GCMs. This paper explores an approach to overcoming the second geographical

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problem in using GCM output for resource analysis. To accomplish this, we use a county-level approximation of the GISS GCM grid to match available resource data to the geographic scale of the GCM. As a demonstration of this approach, we estimate the effect of a possible climate change on soybean agriculture using two simple techniques based on county-level yield data.

2. Methods

Our first step was to formulate a county-level approximation of the GISS GCM grid for the United States. All GISS grid cells that covered any part of the conterminous United States were numbered from 1 to 21 and each county was assigned to the proper grid cell based on the latitude and longitude of the county centroid.

Current soybean yield by grid cell was calculated from the 1978 soybean production (the most recent data available). The GEOECOLOGY data base (Olson et al. 1980 as updated) was our source of county-level environmental data. The grid cell-averaged yield was then calculated as the (county-approximated) grid cell-total production divided by the (county-approximated) total grid cell area.

The temperature and precipitation characterizing areas of major (56.9–299.3 kg/ha), minor (1.6–11.6 kg/ha), and zero yield were calculated from the adjusted station data in the Historical Climatology Network (HCN) (Quinlan et al. 1987). This dataset was compiled at the National Climatic Data Center and contains temperature and precipitation data for 1219 stations in the conterminous United States. The 1978 monthly mean temperature and precipitation data used for these calculations have been corrected for changes in time of observation and instruments, instrument moves, and station relocations (Karl and Williams 1987).

Daily climate data were not available for this analysis; therefore, we estimated growing-season growing-degree days (GDD) and precipitation from monthly data. The growing season in each grid cell was defined as those months (within the interval May–October) when the mean temperature was at least 10°C. Growing-season GDD was estimated as

$$\mathrm{GDD} = \sum_{N=1}^{n} M(T - 10) \qquad (1)$$

where $N = 1 \cdots n$ represents months with mean temperature of at least 10°C; M is number of days in the month (30 or 31); and T is the mean monthly temperature, set to 30°C when it exceeds 30°C. The 10°C and 30°C limits were taken from the GDD calculation for maize (Newman 1980) because maize and soybeans have similar climatic requirements (Hughes and Metcalfe 1972). The growing-season GDD and precipitation calculated from the 1978 climate data, corresponding to grid cells of major, minor, or zero yield, were then compared with the corresponding data calculated from the output of the GISS GCM (10 yr averages of monthly means from simulated years 26–35, by which time the modeled climate is believed to have reached equilibrium [G. Russell,[1] personal communication]). The differences between the control and doubled-$\mathrm{CO_2}$ runs were superimposed onto the values from the 1978 HCN data. Any grid cells whose simulated future GDD and precipitation fell within the current ranges for major yield were assumed to be major production areas, and any grid cells whose simulated future GDD and precipitation fell within the current ranges for minor yield were assumed to be minor production areas; other grid cells were assumed to be zero-production areas.

In a second approach to projecting future soybean production, we used regression coefficients to estimate the change in soybean yield that would result from changes in temperature or precipitation. Thompson (1970) related departures from "normal" weather (1930–68 average for Illinois, Indiana, Iowa, Missouri, and Ohio) to changes in yield and found that the influencing factors were June and August temperature, July–August precipitation, and September–June precipitation. We used these temperature and precipitation projections from the GISS control and doubled-$\mathrm{CO_2}$ climate simulations as input to Thompson's regression:

$$\begin{aligned}\Delta Y = {} & 5.732\,(\Delta\mathrm{JUNT}) - 4.005\,(\Delta\mathrm{JUNT})^2 \\ & - 6.303\,(\Delta\mathrm{AUGT}) - 1.794\,(\Delta\mathrm{AUGT})^2 \\ & + 64.586\,(\Delta\mathrm{JULP}) - 2.459\,(\Delta\mathrm{JULP})^2 \\ & + 43.532\,(\Delta\mathrm{AUGP}) - 2.567\,(\Delta\mathrm{AUGP})^2 \\ & + 4.139\,(\Delta\mathrm{WINP}) - 0.665\,(\Delta\mathrm{WINP})^2 \qquad (2)\end{aligned}$$

where ΔY is change in yield (kg/ha), and ΔJUNT and ΔAUGT represent the differences in the doubled-$\mathrm{CO_2}$ and control GISS June and August temperatures in degrees Fahrenheit, and ΔJULP, ΔAUGP, and ΔWINP the differences in July, August, and September–June precipitation in inches, respectively.

However, Thompson's regression expresses yield averaged over the fields in which the soybeans are grown, whereas the regional approach that we used divides the soybean production by all the land in the grid cell, resulting in much lower values of yield for the same amount of production. Thus, we had to adapt the results from Thompson's regression for our use. We did this by calculating any predicted change in yield as a percentage of the most recent (1968) average yield

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[1] Goddard Institute for Space Studies.

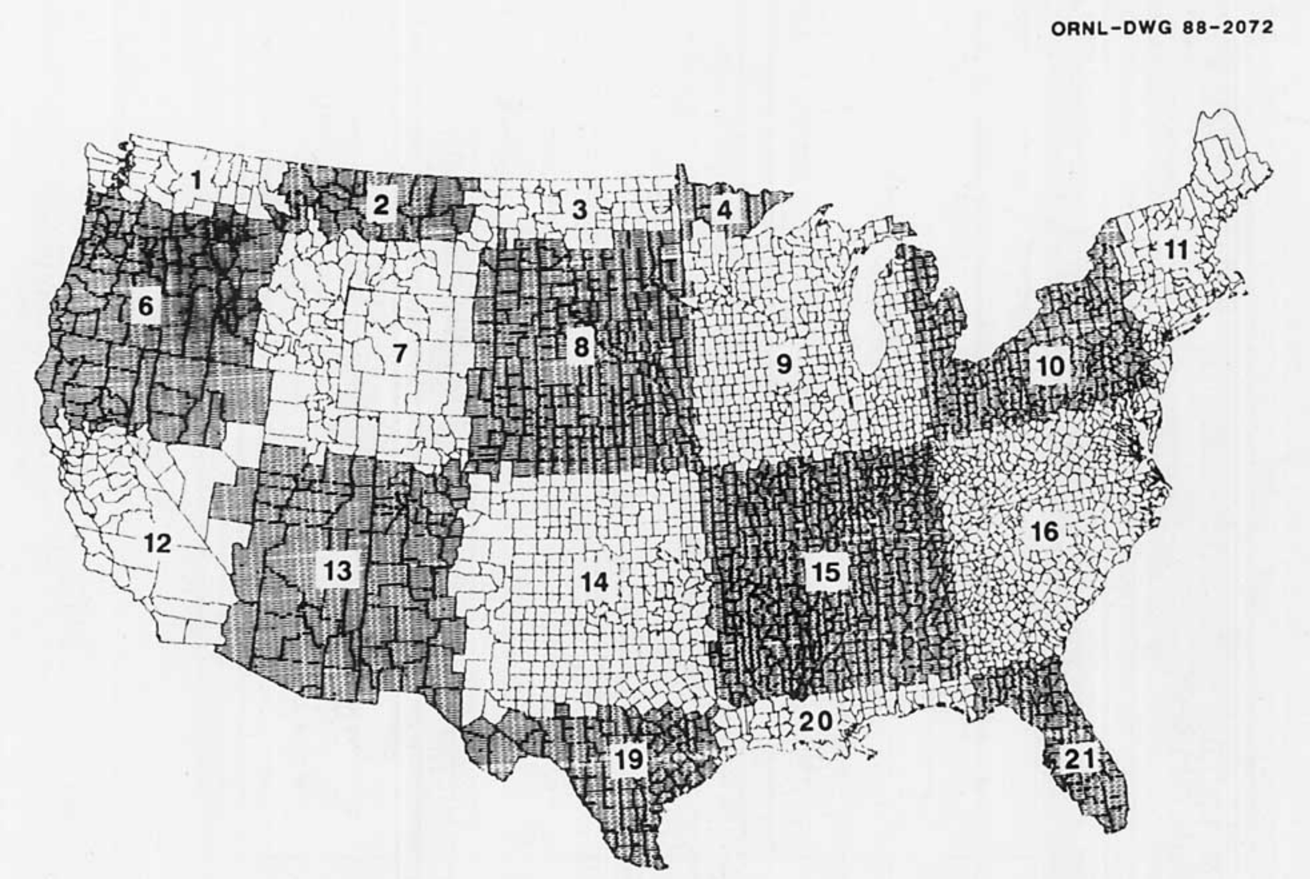

FIG. 1. County approximation to the grid cells of the GISS model II GCM. The numbering of grid cells corresponds to that used in our calculations and results.

in Thompson's paper (1900 kg/ha). We then applied the percent change in yield to the 1978 yield from the GEOECOLOGY dataset to estimate yield by grid cell under the changed climate.

Because Thompson's regression equation is nonlinear, it would have been preferable to 1) estimate the change in yield for the 10 individual years from the GCM output, and 2) take the average of those ten estimates, rather than to introduce a possible bias by basing the estimate on the 10-yr average climate. Unfortunately, the individual years of GCM output can not be assumed to realistically reflect year-to-year climatic variability.

3. Results and discussion

Figure 1 shows the county-level approximation to the GISS grid. The relatively large size of counties in the western United States is reflected in the greater coarseness of the grid approximation in that part of the country. Nevertheless, this county-level grid provides a reasonable fit to the actual GISS grid. (The grid cell assignments for each county are available from the second author, either in printed format or as a SAS data set).[2]

As of 1978, soybean production in the United States was limited to areas east of the 105°W meridian; major production areas were along the lower Mississippi River, Iowa–Minnesota, and Illinois–Indiana–Ohio (Fig. 2). When this distribution is viewed on the scale of the GISS grid (Fig. 3), it can be seen that grid cells 8, 9, 10, 15, 16, and 20 contained major yields (grid cell-averaged yields of 56.9–299.3 kg/ha) and grid cells 3, 11, 14, 19, and 21 contained minor yields (grid cell-averaged yields of 1.6 to 11.6 kg/ha). The remaining grid cells contained no soybean production. Details of soybean yield by grid cell may be found in Table 1.

Grid cells that contained major yields in 1978 were characterized by an estimated 1328–2846 growing-season GDD and 122–249 cm growing-season precipitation (Table 1). The characteristics of the minor-production areas were 1115–2960 GDD and 112–244 cm precipitation. No grid cells were miscategorized; i.e., the range of growing-season GDD and precipitation

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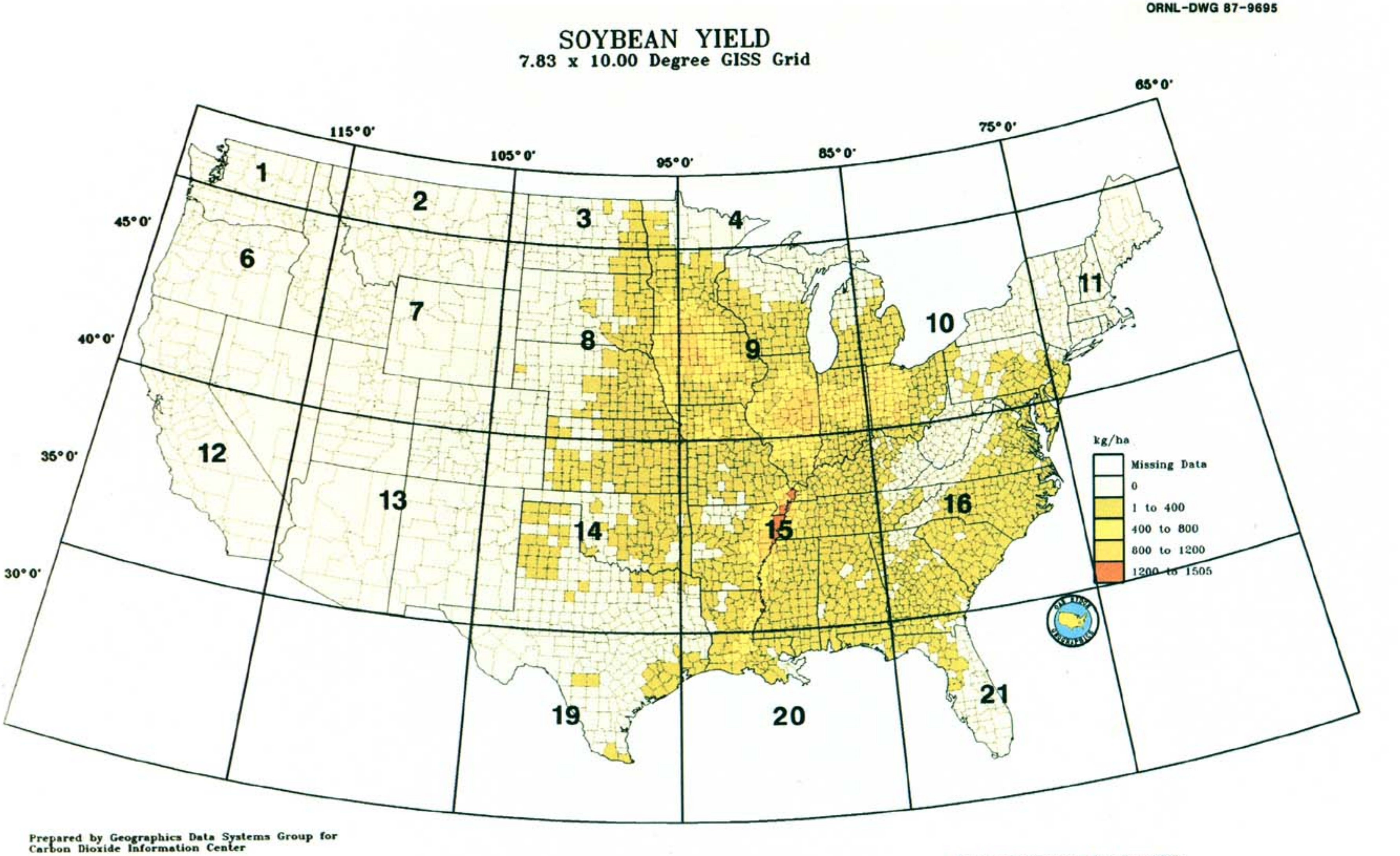
[2] SAS Institute, Inc., Cary, North Carolina.



Prepared by Geographics Data Systems Group for
Carbon Dioxide Information Center

Data Source: Geoecology Data Base, ORNL
Data Date: 1978
Data Limitations:
(1) Averaged on a county basis as crop yield (kg) divided by county area (ha)
(2) Missing data for 27 counties

FIG. 2. County-averaged 1978 soybean yield based on GEOECOLOGY data, with overlay of GISS GCM grid cells.

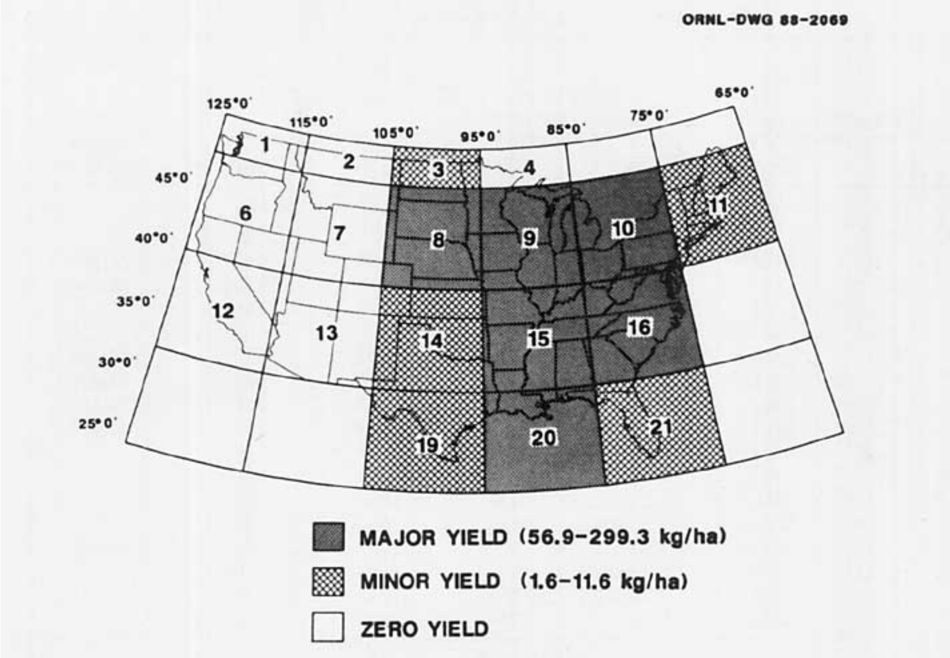


FIG. 3. 1978 soybean yield for the conterminous United States, averaged on the basis of the county-approximated GISS GCM grid.

for major production did not include any grid cells with minor or zero production, and the range for minor production did not include any grid cells with zero production.

Comparison of estimated GDD and precipitation using the simulated doubled-CO_2 climate with that using the 1978 climate suggests that the production of soybeans would shift northwards and eastwards (Fig. 4a). The western states remain nonproducers because of insufficient growing-season precipitation, and the southern states become nonproducers because of excessive growing-degree days. Based on climate changes simulated by the GFDL GCM, Rosenberg (1986) also suggested that soybeans could be forced northward. He noted that this could result in a shift to less fertile soils; thus, climate and other environmental factors might not all be advantageous simultaneously, and overall production could be adversely affected. Other studies have related changing climate to shifts in cropping zones. For example, such shifts have been described for North American wheat (Rosenzweig 1985) and corn (Newman 1980; Blasing and Solomon 1984) for possible future climatic changes. Hammer et al. (1987) wrote that an observed expansion of wheat cropping in Australia was possibly related to a recent change in climate.

The regression analysis suggests that soybean yield would decline in all currently producing grid cells (Fig. 4b). Among those grid cells with current major production, the projected percent of decline ranges from 2% (grid cell 16) to 15% (grid cell 8); among current minor-production grid cells, the percent of decline ranges from 3% (grid cell 3) to 24% (grid cell 19) (Table 1). Of course, this approach does not account for potential yield in grid cells not currently producing soybeans.

Similar potential yield decreases have been projected for North America by other investigators. Waggoner (1983) analyzed the effects of a 1°C increase in temperature and a 10% decrease in precipitation (which he characterized as "a reasonable consequence of a CO_2 increase and climate change"). He projected decreases in yield of wheat from 2% (Oklahoma) to 12% (North Dakota), of corn from 3% (Iowa and Illinois) to 4% (Indiana), and of soybeans from 4% (Illinois) to 7% (Iowa). Stewart (1988), in his analysis of the effects of the GISS doubled-CO_2 climate on spring wheat in Saskatchewan, projected decreases in yield of 6% to 28%. Not all projections of the effects of changing climate on crop yields are negative. For example, Kettunen et al. (1988) reported that, under the GISS doubled-CO_2 climate, spring wheat yields in Finland could increase by an average of 6% to 20%.

There is general consistency between our two sets of results. For the eight grid cells with the greatest percentage decline according to the regression analysis (ranging from 12% to 24%), production either remains in the same category or drops to the nonproducer category. However, for grid cell 11, with an 8% decline based on the regression analysis, production increases from minor to major. Given the two approaches, it is not surprising that the two sets of results disagree in one case where the predicted change is small, but agree where the predicted changes are large.

TABLE 1. Soybean yields and growing-season climate by grid cell.

	1978 soybean yield[a]		1978 growing-season climate[b]		Simulated future growing-season climate[c]		Future potential yield level[h]	Future potential change in yield[i]
Grid cell[d]	kg/ha	Level[e]	GDD[f]	GSP[g]	GDD	GSP		
1	0		836	83	1433	98		
2	0		828	98	1515	104		
3	1.6	Minor	1115	112	1634	118	Minor	−3%
4	0		885	180	1354	190	Major	
6	0		1051	55	1979	64		
7	0		804	32	1531	63		
8	71.7	Major	1479	122	2242	122	Major	−15%
9	299.3	Major	1450	171	2145	185	Major	−13%
10	103.0	Major	1328	136	2063	158	Major	−12%
11	3.2	Minor	1124	137	1693	158	Major	−8%
12	0		2104	10	2941	9		
13	0		1841	44	2703	44		
14	7.2	Minor	2386	119	3026	117		−18%
15	167.0	Major	2286	172	3075	177		−13%
16	56.9	Major	2069	171	2792	184	Major	−2%
19	5.2	Minor	2960	149	3403	150		−24%
20	114.8	Major	2846	249	3348	253		−13%
21	11.6	Minor	2934	244	3515	247		−16%

[a] Grid cell-averaged data.
[b] Based on data from the Historical Climatology Network.
[c] Based on differences between GISS GCM doubled-CO_2 and control runs superimposed on 1978 climate.
[d] Numbering of grid cells as in figures and text.
[e] Major = 56.9–299.3 kg/ha, minor = 1.6–11.6 kg/ha.
[f] Growing-degree days (°C-days).
[g] Growing-season precipitation (cm).
[h] Based on simulated future growing-season climate; yield levels as in footnote (e).
[i] Based on differences between GISS GCM doubled-CO_2 and control runs, using weather-yield regression.

Using the two different approaches, we have arrived at two somewhat different but certainly not mutually exclusive estimates of possible future soybean production, as determined by a simulated climate change from a doubled concentration of atmospheric CO_2. On the one hand, where soybeans are currently grown, production might decline because of more adverse weather conditions (the extrapolation from the regression analysis). On the other hand, soybean agriculture might migrate northwards and eastwards (the projection from the comparison of simulated current and future values of growing-season GDD and precipitation).

There are several important qualifications to the results of the analyses presented in this paper. These analyses assume that the GISS GCM correctly simulates current and future climate. Both methods of analysis presented here depend, of course, on valid projections of the future climate. It is beyond the scope of this paper to attempt to validate the climate simulations of the GCMs; indeed, much effort has been expended elsewhere toward that end (e.g., Schlesinger and Mitchell 1987). The climate patterns simulated by a single model should only be accepted with the understanding that other models may give different results in terms of global averages and regional patterns. In general, it has been found that the GCMs reproduce temperature patterns better than precipitation patterns, and that the simulations become more questionable when finer-scale regional patterns are considered. Certainly, the accuracy of resource analyses based on climate simulations will be no better than that of the climate simulations themselves. At this point, it is not obvious how simulated future climates from GCMs should be used in resource analyses when it is known that the GCM simulations of the current climate are not entirely accurate. One approach is to use the difference between the control and doubled-CO_2 climate simulations; another approach is to literally accept the simulated future climate. We have used the former approach in this paper for the purpose of demonstration.

Many factors in addition to those considered in this paper affect soybean production: soil type, disease and insects, technology (including fertilization), and solar radiation (Ravelo and Decker 1981). Terrain, shorter-term climatic factors such as the distribution of precipitation within the growing season, or climate variability on a finer scale than that of the GCM grid, could also be important factors in determining actual production.

It should also be appreciated that soybean production in the United States is a relatively recent phenomenon compared with the production of corn or wheat,

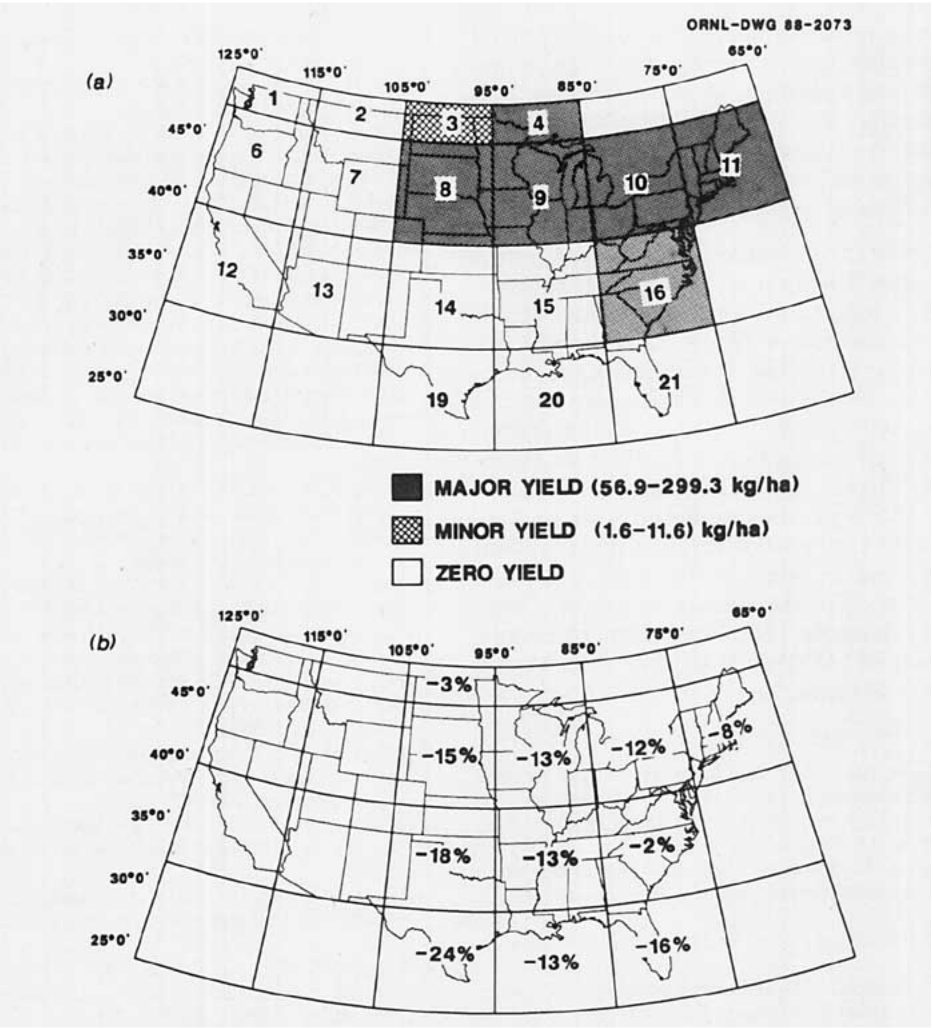


FIG. 4. Potential future soybean yield under the GISS GCM doubled-CO_2 climate: (a) categorized as major or minor based on temperature and precipitation regimes associated with current yield levels; (b) projected percent change from 1978 levels in soybean yield based on regression analysis.

for example. Soybean production was stimulated by the introduction of many varieties by the U.S. Department of Agriculture starting in 1898, and production increased sharply during World War II because of the demand for oil (Hughes and Metcalfe 1972). Rosenberg (1986) anticipates that soybean production will likely spread westward as new drought-resistant varieties are developed. Thus, the distribution and production of soybeans has probably not yet equilibrated with current environmental factors. The use of regression analysis to predict the impact of climate change on crop yields is questionable because factors that influence current-season yields may not be as relevant on longer time scales [because introduction of new varieties and technologies—possibly, even, during the two decades that have elapsed since the publication of Thompson's (1970) paper—are not included, and because the effects of extreme episodic weather events are not considered (Rosenberg 1986).] Also, a weather-yield regression may only be valid for the location in which the underlying data were collected. Furthermore, analyses based on climatic factors alone do not reflect any future changes in soybean distribution or yield attributable to the direct fertilization effects of the increased atmospheric CO_2 (e.g., Rogers et al. 1983) or interactions between climate change and fertilization from CO_2. Acock and Allen (1985), citing Kimball (1983), reported a 17% mean increase in marketable yield of soybeans when exposed to a doubling of atmospheric carbon dioxide. Also, analyses based solely on climatic factors do not account for other mechanisms such as changes in the availability of surface water or groundwater for irrigation.

For these reasons, the analysis presented in this paper should not be considered as a prediction of future conditions but rather as an illustration of an approach to the analysis; a more authoritative analysis will depend on a more complete understanding of the agronomic factors determining soybean production. However, this paper does illustrate that it is possible to match environmental data on a county level to the gridded output from a climate model as one approach to analyzing the potential effects of climate change on resources.

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REFERENCES

Acock, B., and L. H. Allen, Jr., 1985: Crop responses to elevated carbon dioxide concentrations. *Direct Effects of Increasing Carbon Dioxide on Vegetation,* B. R. Strain and J. D. Cure, Eds., DOE/ER-0238, U.S. Dept. of Energy.

Blasing, T. J., and A. M. Solomon, 1984: Response of the North American corn belt to climatic warming. *Prog. Biometeorol.,* **3,** 311–321.

Clark, W. C., 1985: Scales of climate impacts. *Climatic Change,* **7,** 5–27.

Cohen, S. J., 1986: Impacts of CO_2-induced climatic change on water resources in the Great Lakes Basin. *Climatic Change,* **8,** 135–153.

Gates, W. L., 1985: The use of general circulation models in the analysis of the ecosystem impacts of climatic change. *Climatic Change,* **7,** 267–284.

Hammer, G. L., D. R. Woodruff and J. B. Robinson, 1987: Effects of climatic variability and possible climatic change on reliability of wheat cropping—a modelling approach. *Agric. Meteor.,* **41,** 123–142.

Hansen, J., G. Russell, D. Rind, P. Stone, A. Lacis, S. Lebedeff, R. Ruedy and L. Travis, 1983: Efficient three-dimensional global models for climate studies: Models I and II. *Mon. Wea. Rev.,* **111,** 609–662.

——, A. Lacis, D. Rind, G. Russell, P. Stone, I. Fung, R. Ruedy and J. Lerner, 1984: Climate sensitivity: Analysis of feedback mechanisms. *Climate Processes and Climate Sensitivity,* J. E. Hansen and T. Takahashi, Eds., Maurice Ewing Series, **5,** American Geophysical Union, 130–163.

Hughes, H. D., and D. S. Metcalfe, 1972: *Crop Production,* third ed., MacMillan, 627 pp.

Karl, T. R., and C. N. Williams, Jr., 1987: An approach to adjusting climatological time series for discontinuous inhomogeneities. *J. Climate Appl. Meteor.,* **26,** 1744–1763.

Kettunen, L., J. Mukula, V. Pohjonen, O. Rantanen and U. Varjo, 1988: The effects of climatic variations on agriculture in Finland. *The Impact of Climatic Variations on Agriculture, Volume 1: Assessments in Cool Temperate and Cold Regions,* M. L. Parry, T. R. Carter, and N. T. Konijn, Eds., Kluwer Academic Publishers, Dordrecht, The Netherlands, 511–614.

Kimball, B. A., 1983: Carbon dioxide and agricultural yield: An assemblage and analysis of 770 prior observations. WCL Rep. 14, U.S. Water Conservation Laboratory, Phoenix.

Newman, J. E., 1980: Climate change impacts on the growing season of the North American "corn belt." *Biometeorol.,* **7**(2), 128–142.

Olson, R. J., C. J. Emerson and M. K. Nungesser, 1980: GEOECOLOGY: A county-level environmental data base for the conterminous United States, ORNL/TM-7351, Oak Ridge National Laboratory, Oak Ridge.

Quinlan, F. T., T. R. Karl and C. N. Williams, Jr., 1987: United States Historical Climatology Network (HCN) serial temperature and precipitation data, NDP-019, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge.

Ravelo, A. C., and W. L. Decker, 1981: An iterative regression model for estimating soybean yields from environmental data. *J. Appl. Meteor.,* **20,** 1284–1289.

Rogers, H. H., J. F. Thomas and G. E. Bingham, 1983: Response of agronomic and forest species to elevated atmospheric carbon dioxide. *Science,* **220,** 428–429.

Rosenberg, N. J., 1986: Adaptations to adversity—agriculture, climate and the Great Plains of North America. *Great Plains Quart.,* **6,** 202–217.

Rosenzweig, C., 1985: Potential CO_2-induced climate effects on North American wheat-producing regions. *Climatic Change,* **7,** 367–389.

Schlesinger, M. E., and J. F. B. Mitchell, 1987: Climate model simulations of the equilibrium climatic response to increased carbon dioxide. *Rev. Geofis.,* **25,** 760–798.

Solomon, A. M., 1986: Transient response of forests to CO_2-induced climate change: Simulation modeling experiments in eastern North America. *Oecologia,* **68,** 567–579.

Stewart, R. B., 1988: Climatic change: Implications for agricultural productivity on the Canadian prairies. *Preparing for Climate Change,* Government Publishers, 409–419.

Thompson, L. M., 1970: Weather and technology in the production of soybeans in the central United States. *Agron. J.,* **62,** 232–236.

Waggoner, P. E., 1983: Agriculture and a climate changed by more carbon dioxide. *Changing Climate,* National Academy Press, 383–418.

White, M. R., Ed., 1985: *Characterization of Information Requirements for Studies of CO_2 Effects: Water Resources, Agriculture, Fisheries, Forests and Human Health,* DOE/ER-0236, U.S. Dept. of Energy.