CLIMATE CHANGE AND U.S. AGRICULTURE: SOME FURTHER EVIDENCE

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There have been a number of previous studies of the effects of climate change on U.S. agriculture (e.g., d'Arge, 1975; Kokoski and Smith, 1987; Dudek, 1988; Adams, et al., 1988; Adams et al., 1990, 1995; Mendelsohn et al., 1994). These studies differ in terms of their procedures, geographical coverage, climate change assumptions and databases. Nonetheless, they provide a methodological basis for studying the impacts of climate change on the agricultural sector. Also, among the more recent studies, common findings are emerging which provide some guideposts in the evolving policy debates regarding climate change (Schimmelfennig and Lewandrowski (1997) and Adams et al. (1998)).

Despite the central tendencies displayed in current studies, there are some important shortcomings. First, they have almost exclusively focused on conventional agricultural crops such as grain (e.g., corn and wheat and soybeans) either omitting other crops or assuming their climate response is the same as the major crops mentioned above. Results of these studies suggest that some regions of the U.S., such as the Southeast and Southwest, may suffer substantial economic losses if production of grains shifts to more northerly latitudes. However, since these Southern regions are major producers of heat tolerant crops such as cotton, sorghum, fruits and vegetables. Ignoring thier potentially differntial climatic response may overstate potential economic losses. In addition, direct effects of climate change on livestock weight gain and other performance measures have not been addressed.

Second, the role of adaptations have not been explored in any systematic way. There are many ways that farmers may be able to adjust. For example, farmers may be able to adjust planting and harvest dates, production processes, inputs and crop mixes in the face of climate change. Introduction of new technology may also provide an important buffer against climate change. Crops may also migrate from warmer areas into areas experiencing warming.

A few recent studies illustrate the importance of adaptation (Kaiser et al., 1993; Mendelsohn et al., 1994), but they do not evaluate whether adding more adaptation options matters in terms of changes in broad economic welfare measures. Other studies (CAST, Crosson) discuss the prospects for crop migration and research targeted to adaptation options (e.g., plant breeding for high temperature tolerance, drought tolerance), both for current crops and in-migrating crops. However, these studies do not provide estimates of migration possibilities or evidence regarding potential payoff from research targeted specifically at climate change.

Third, previous studies do not consider the economic effects of changes in forage production on range land forage production or livestock performance. (The climate change assessments by Adams et al. (1990, 1993a) do allow for some changes in the productivity of pasture and haylands, which in turn change livestock/feed balances.) Extreme temperatures affect livestock performance (e.g., reduction in weight gain per unit of food intake). Thus, even if precipitation is not reduced, temperature increases beyond some level will reduce performance and increase the time required for cattle and other livestock to reach given weight levels. Such changes in livestock weight gain affect the profitability of livestock enterprises. Since livestock amount to about one-half of total farm-gate value of agricultural production in many states, changes in livestock/feed relationships may have a substantial economic impact.

The research reported here was designed to extend previous economic analyses of climate change on agriculture to address the limitations mentioned above. Specifically, (1) incorporating climate change sensitivity of more heat tolerant rather than assuming they respond as do corn, soybeans and wheat; (2) considering the impacts of farmer adaptations to climate change; (3) allowing for crop migration into regions where those crops are not currently being grown; (4) incorporating changes in forage production and livestock performance; and (5) assessing the potential for technological change to offset climate change. The research was also designed to estimate how much such omissions "matter" in terms of the magnitude and stability of the estimates.

The basic model used here is the Agricultural Sector Model (ASM). ASM is a spatial equilibrium model of the U.S. agricultural sector, which has been used in many analyses of the interaction between agriculture and the environment, including several pieces on climate change such as Adams et al. (1990, 1993a).

For this research, additional changes to ASM have been made. First, citrus and tomatoes (a proxy for vegetable production in general) have been added to the model. Incorporating these crops allows an analysis of the effect of climate change on selected high-valued fruits and vegetables that might benefit from temperature increases. Second, the model has been modified to allow migration of crops (northward) into other production areas. The treatment of farmer adaptations, changes in livestock performance, adjustments in water availability and changes in exports of U.S. agricultural commodities, while important components of this assessment, are handled by adjustments in existing coefficients and parameters of the model. Finally, a dynamic component was adapted from a related model (Adams et al 1993b), allowing simulations into the future (for the 2060 analysis).

Overview of the Agricultural Sector Model (ASM)

The ASM is a spatial equilibrium model formulated as a mathematical programming problem (Takayama and Judge, 1971). The model represents production and consumption of primary agricultural products including both crop and livestock products. Processing of agricultural products into secondary commodities is also included. The production and consumption sectors are assumed to be made up of a large number of individuals, each of whom operates under competitive market conditions. This leads to a model which maximizes the area under the demand curves less the area under the supply curves. This area can be interpreted as a measure of economic welfare equivalent to the annual net income lost or gained by agricultural producers and consumers as a consequence of global climate change, expressed in 1990 dollars. Both domestic and foreign consumption (exports) are included.

The model integrates a set of micro or farm-level crop enterprises for multiple production regions which capture agronomic and economic conditions with a national (sector) model. Specifically, producer-level behavior is captured in a series of technical coefficients that portray the physical and economic environment of agricultural producers in each of the 63 homogeneous production regions in the model, encompassing the 48 contiguous states. These regions are then aggregated to 10 macro regions, as defined by the U.S. Department of Agriculture (USDA). Like earlier studies, irrigated and non-irrigated crop production and water supply relationships are included in the analysis. Availability of land, labor and irrigation water is determined by supply curves defined at the regional level. Farm-level supply responses generated from the 63 individual regions are linked to national demand through the objective function of the sector model, which features demand relationships for various market outlets for the included commodities (see Chang and McCarl, 1993 or Chang et al, 1992, for more details on ASM).

Features have been added to the ASM model to allow dynamic updating. These involve the ability to project yields, domestic demand, import and exports for major commodities. Quantities of cropland, pasture, AUMs, labor, and water as well as the prices of inputs are also projected. The basic mechanisms for this updating fall in two classes: items that are updated based on time (trends) and those updated based on yield changes. The time updated items include yield levels, demands, import levels and supplies and quantities of available inputs. In all cases these are updated by a formula (1+ri)t where ri is the annual rate of change for item i.[2]

The other major updating feature involves input adjustments related to yield levels. Such updating is done for crop input uses, livestock feed use and livestock input uses using an elasticity expressing the response of input usage to a percentage change in yield. Input usage is changed by the percentage change in yield times that elasticity. Elasticities are based on (1) results derived by Evenson and (2) estimation from a 15 year period (from the mid '70s to the early '90s) from selected crops. Livestock feed use is assumed to be directly proportional to yield increases.

Climate Change Scenarios

Two general classes of climate change scenarios are used; the first are uniform temperature and precipitation changes across regions of the U.S. and the second are GCM-based forecasts, which allow for regional differences in climatic change. Both types of climate change scenarios are used in recent studies. This allows us to test the sensitivity of the economic estimates to the type of climate change scenario imposed by the analyst.

These scenarios are imposed on two states of the agricultural economy, one representing the present (1990) and the other a future configuration of the agricultural sector (2060). The 2060 assessment requires estimates of commodity demand, resource availability and agricultural yields in the absence of climate change. Forecasts of these parameters are obtained with the dynamic updating procedure described in Section 3. Given the challenges involved in making economic forecasts over such a lengthy time horizon, caution should be exercised in interpreting results from the 2060 analysis.

The uniform incremental scenarios include 16 combinations of alternative temperature and precipitation changes (0, 1.5EC, 2.5EC and 5.0EC for temperature; and -10%, 0%, 7% and 15% for precipitation). In addition, four alternative levels for atmospheric CO_2 concentrations (355, 440, 530 and 600 ppm) are considered. This leads to a total of 64 (4X4X4) uniform incremental scenarios (including no change in temperature and no change in precipitation). These 64 scenarios comprise the basis for the estimation of a climate change "response function" for 1990 and 2060 conditions. This function allows one to test the sensitivity of economic welfare (the objective function value form ASM) to changes in temperature, precipitation or CO_2.

Since it is not possible to assign probabilities to any specific climate forecast, two cases which may capture the middle range of effects are evaluated in detail. The first, and perhaps optimistic case assumes a uniform incremental change of 2.5EC temperature change, a 7% precipitation increase and a 530 ppm atmospheric CO_2 concentration. The other case is a uniform incremental change of 5.0EC in temperature with no change in precipitation, while maintaining the 530 ppm atmospheric CO_2 concentration assumption. These two "case studies" are used in a series of sensitivity analyses concerning the role of farmer adaptations, changes in export (world food production), and other key assumptions.

The two GCM-based climate change forecasts are from GISS and GFDL-R30. The GISS forecasts offer a useful point of comparison with some previous economic analyses of climate change. Specifically, the effects of GISS climate forecasts on U.S. agriculture were recently assessed by Adams et al. (1995). Given that Adams et al. (1995) used a version of ASM, a comparison of economic effects obtained here and the results reported in Adams et al. (1995), indicate whether the changes (in adaptation and mitigation opportunities) made to ASM as part of this research add to the implications gleaned from the earlier study. The second GCM-based climate forecasts for which yield data are available (GFDL-R30) is not the same GFDL climate forecast employed by Adams et al. (they used GFDL-QFLUX). GFDL-R30 forecasts a somewhat harsher climate change for the U.S. than GFDL-QFLUX. This lead to some sharp differences in crop yield projections between the GFDL data used in Adams et al. (1995) and those used in the present study. Thus, resulting economic estimates for GFDL-R30 can not be compared to the GFDL estimates reported in Adams et al. (1995).

Predicted Changes in Crop and Forage Yields and Livestock Performance

A basic input into ASM is the yield level (output per acre) for each crop (including forage) in the model. The effects of climate change are modelled primarily as changes in these yield levels.[3] Estimates of yield changes were developed here using a variety of methods, including crop simulation models, a plant-soil ecosystem model and regression analysis. In addition, a nutritional balance model was used for estimates of changes in livestock performance. A description of the methodologies used in each of these analyses is given below.

Crop Yield Changes

Major Grains

Estimates of yield changes for wheat, corn and soybeans were generated using the SOYGRO (Jones et al., 1988), CERES-Maize (Ritchie et al., 1989) and CERES-Wheat (Godwin et al., 1989) dynamic crop simulation models. Seventeen sites were selected to represent the major agroclimatic regions in the U.S. Thirty years (1951-80) of daily climate data were used to produce estimates of current yield and irrigation demand at each site. Simulations were then conducted for each crop at each site for all combinations of changes in temperature, precipitation and atmospheric CO_2 concentration.

At the base CO_2 level of 355 ppm, all three crops experienced yield decreases with increasing temperatures, although the magnitudes of the reductions varied by crop. Additionally, demand for water is increased. With increased CO_2 levels, improvement is seen in maize and wheat yields, but not enough to offset the negative impacts of the higher temperatures. Because soybeans have a higher positive yield response to increased CO_2, the negative impacts of increased temperature are offset to a greater degree for soybeans than for wheat or maize.

Yield changes for the GCM-based climate forecasts varied dramatically across regions. For example, corn (maize) yields in the Corn Belt decreased by 34 percent under GFDL-R30 while in the Delta region, there was no change in corn yields (from the base). Similarly, soybean yields in the Corn Belt decreased by 29 percent under GFDL-R30, while in the Lake States they increased by 47 percent. All of these changes include the CO_2 effect on yields; as with the uniform climate change scenarios, increases in CO_2 mitigate some of the negative effects of climate change in isolation.

Cotton and Sorghum

In most previous work, yield changes for many important crops such as cotton, sorghum and hay, were either not included or assumed to follow the pattern for corn, wheat and soybeans. For this study, specific yield change estimates for cotton and sorghum (and hay) were generated using EPIC (Erosion Productivity Impact Calculator), is a simulation model developed to determine the relationship between soil erosion and soil productivity (Williams et al., 1984). EPIC simulates these processes, as well as crop yields.

As with the grain crops, cotton and sorghum yields were simulated for the temperature-precipitation-CO_2 combinations and for the GCM-based climate changes at each of the six locations. The predicted yield response of cotton and sorghum to climate change and changes in atmospheric CO_2 were similar in terms of direction of change. Cotton and sorghum yields increased as CO_2 and precipitation increased, and decreased as temperature increased. Yields decreased as temperature increased because the crop reached its maturity in fewer days, i.e., a shorter growing season results in fewer and/or smaller seeds or fruit. Irrigation water use decreased as rainfall increased. Irrigation water use also decreased as CO_2 increased because increased CO_2 increases crop water use efficiency. Most of the climate scenarios resulted in less water use than the baseline.

Tomatoes, Citrus and Potatoes

The yield change estimates for fruits (tomatoes, oranges) and vegetables (potatoes) were estimated with crop simulation models.

Citrus simulations were run for 8 sites where citrus is currently grown commercially and 14 potential sites. The results indicate that temperature increases may cause some decrease in production in the southern-most producing sites primarily due to the shortening or complete lack of a dormant period required for acceptable yields in citrus. However, some increases in yields at more northerly (current) sites were observed. This suggest that a slight expansion of area of citrus production could occur, although many regions which may develop climates suitable for citrus production will not have the sandy, well-drained soils such trees require.

Simulations of yield changes for potatoes were performed using SIMPOTATO, a physiologically-based model (Hodges et al., 1992). Temperature increases above base temperatures caused a decline in potato yields, due to sensitivity of tuber formation and growth. Finally, yield changes for tomatoes were based on an adaptation of a generic crop simulation model, CROPGRO (Hoogenboom et al., 1992). As temperature increased, simulated yield increased in most cases to an optimum of 2.5EC above actual means.

Yield Changes with Adaptation

The estimated yield changes discussed above assume that farmers use current management practices. Two approaches were used to estimate how yields might change if adjustments in cultural practices and technology occur. Both employ regression estimates of observed yield changes as caused by climate differentials. The first approach uses state level pooled data on yields, temperature differentials, soil differentials and research expenditures (as well as other variables) to examine the extent to which crops can migrate geographically in response to climate differentials and the extent to which research (e.g., plant breeding research) can be expected to mitigate negative impacts of climate change (Evenson). The second approach is based on neoclassical duality theory. It uses county-level cross-sectional data on yields, output prices, seasonal temperatures, seasonal precipitation levels and soil characteristics (as well as other variables) to estimate how yields vary with temperature and precipitation.[4] These two approaches are explained in more detail below.

The Role of Crop Migration and Agricultural Research

When a change in temperature, CO_2, or other environmental factor occurs, crop yields will change in the short run. Over time, two factors will modify these short run yield changes. The first is crop migration and/or expansion of the range over which crops are grown. The current pattern of crop production in different temperature/soil (edaphic) regions reflects the comparative advantage of different crops. A rise in temperature may induce crop migration. For example, crops currently produced in warmer locations may migrate "northward" as temperatures rise in cooler regions to levels now experienced in warmer locations. This migration will be limited by edaphic and rainfall conditions which serve as "barriers" to the crop migration induced by temperature changes.

The second factor that will modify short run yield changes is the responsiveness of the research system (both public and private. Plant breeders can put more weight on temperature tolerance of plants in their selection strategies. They can also facilitate crop migration through programs to achieve tolerance to different edaphic and rainfall conditions.

There is no direct evidence regarding the likely scope for yield loss modification via these two factors.. It is possible, however, to draw some inferences from indirect evidence associated with yield variance across regions where temperature, soils and rainfall differ. If there are few temperature and soil barriers to the transmission of a technological improvement realized in one state to other states differing in temperature and soil conditions, then historical yield changes will be highly correlated between states. If these barriers are high, yield changes will not be transmitted from one state to another.

A yield transmission equation was specified and its parameters estimated using crop production data for 20 U.S. states for the 1956-86 period. Estimates for 4 crops (wheat, corn, soybeans and cotton) were obtained. The estimates showed that yield transmission over temperature barriers was consistent with the short run biophysical crop yield estimates when only temperature barriers were included in the specification. However, when soils barriers were also included, the temperature effects on transmission were small. This indicates that crops will migrate easily (i.e., without substantial yield losses) within the same soils-geo-climate zone. For corn and cotton, research programs enhanced transmission indicating that research programs are likely to respond to temperature rises at least for these two crops even if crop migration does not occur. The estimates for the soils barrier, on the other hand, showed significant yield transmission losses across these barriers except for soybean, where they were small. Research programs did not enhance transmission over the soils barriers.

These results suggest that the key barriers to yield transmission with existing varieties are the geoclimate barriers. Thus, it seems likely that most crops (except possibly soybeans) will not migrate large distances; i.e., across entire regions. However, movement from subregion to subregion, where varieties are already genetically similar, may occur. In particular, migration might be expected along the northern frost borders, since there is room for this migration without crossing multiple geoclimate boundaries. The results also suggest, however, that research systems may be quite important in mitigating temperature effects within regions. This will effectively limit incentives to migrate crops. As a result, in this analysis, crop migration is limited to relatively small movements (200 miles) from present crop production areas.

Duality-based Estimates

The second approach to estimating adjustment possibilities is based on neoclassical duality theory. Neoclassical producer theory provides a prediction of how producers (farmers) make production decisions in response to exogenous factors, such as input and output prices, and environmental and technological constraints. Duality theory provides a methodology for predicting those decisions from observations on producers' costs or profits.

Using neoclassical theory, the long-run effect of a climate change can be estimated in one of two ways. First, a supply or yield function can be estimated directly with data containing observations on yields, input and output prices, site characteristics and climate variables. Alternatively, the economic impact can be predicted from an estimated profit or cost function. Only estimates based on the direct estimation of the yield equations will be discussed since these are the estimates that provided input into the adaptation runs of ASM.

Yield equations were estimated for corn, wheat and soybeans using county-level data from the 1987 Census of Agriculture for 12 midwest states. The functional form was quadratic in the climate variables (seasonal temperature and precipitation) to allow for non-monotonicity but linear in all other terms where monotonicity would be expected (e.g., output prices). The estimated equations were then used to predict yield changes under the alternative climate scenarios. The estimates all assume the 1987 level of CO_2. For each crop-scenario combination, we estimated the yield change at 5 counties in the midwest corresponding to the midwest sites used in deriving the short-run estimates of yield changes for corn, wheat and soybeans based on biophysical crop models. Comparison of these estimates provides an indication of the extent to which farmers can be expected to adjust their production processes to mitigate negative impacts of climate change.

The results suggest that mitigation is possible, particularly for corn and wheat. For both crops, temperature increases averaged over the sites growing that crop induced long-run yield reductions that were smaller than the short-run estimates. The differences in the short-run and long-run estimates were larger for a 2.5EC warming than for a 5.0EC warming, indicating a greater potential for adaptation to mitigate negative impacts for smaller temperature increases.

The results for precipitation increases differ in that the general result was that the long-run estimates were more pessimistic than the short-run biophysical estimates, with the exception of soybeans. In general, the short-run estimates indicate that increased precipitation will increase yields. The long-run yield changes estimated from the yield equations were generally less positive and in some cases negative. The negative impacts reflect the fact that in the estimated yield equations, increases in April precipitation were generally yield-reducing. In addition, the differences between the two sets of estimates may be attributable to differences in the treatment of irrigation.

While the above methodology provided site-specific estimates of yield changes, the estimates for any individual site-crop-climate combination are not sufficiently precise to provide substitutes for the short-run estimates. As a result, we combine information from three sources to provide a rough estimate of the magnitude of the effect of adaptation. The first is a comparison of the short-run and long-run yield change estimates discussed above (i.e., a comparison of the biophysical estimates and the estimates from the estimated yield equations). The second is information on adaptation potential based on alternative runs of the biophysical simulation models under varying assumptions about adaptation already present in the models (e.g., changes in planting dates). The third source of information is an analysis regarding the potential for adjustment through technological change.

While adaptation is site and crop specific, this collection of information indicates that a reasonable first approximation is that adaptation could potentially offset roughly half of the negative yield impacts of a moderate climate change. However, the evidence suggests that adjustment possibilities are smaller for larger temperature changes. No evidence is available on the potential for adaptation to further enhance positive impacts. Based on these conclusions, the adaptation runs of ASM incorporate the following changes: (1) for the 2.5EC scenario, negative yield change estimates derived from the biophysical models are reduced by one-half, and (2) for the 5.0EC scenario, negative yield change estimates are reduced by 25 percent. No adjustments are made when predicted yield change estimates from the biophysical models were positive. These changes are applied to all crops in all regions of ASM.

Changes in Forage Production and Livestock Performance

Estimates of yield changes on pastureland were obtained from two sources. Estimates for the south were generated using the EPIC crop simulation model (described above). Estimates for natural (unimproved) grassland sites west of the Mississippi River were generated using a plant-soil ecosystem model (Ojima). These two sets of estimates were then combined to provide estimates of forage changes for all regions within ASM.

EPIC was used to simulate bermuda grass yield response to climate change and changes in atmospheric CO_2 for the 64 weather scenarios at seventeen locations. Crop growth was simulated for 30 years for each climate scenario at each location. Yield response of improved pasture to climate change and changes in atmospheric CO_2 varied by location. All improved pastureland was assumed to be rainfed, so no water demands were estimated.

The forage changes in the western U.S. were estimated using the CENTURY model (Parton et al., 1987). The model simulates the dynamics of grassland systems, and implements land management options that influence the level of grazing, fire frequency and N deposition. To analyze the sensitivity of grassland ecosystems to modified climate and atmospheric CO_2 levels, simulations were performed for 12 grassland sites west of the Mississippi River.

At all sites, increases in precipitation were predicted to increase net primary production. The temperature effect did not display a consistent pattern of changes in net primary production (vegetative yields, measured in grams per square meter). Some sites had a negative response to temperature changes, indicating that as temperature increases net primary production declines while other sites responded positively to increased temperature. The overall effect of CO_2 increases across sites was positive.

The location-specific estimates of changes in forage production generated for the south and for the western sites were used to estimate regional changes in forage production for the production regions in ASM. Forage production for each simulated site was converted to lbs/ac expected from each climate scenario. Percentage changes were calculated by comparisons with the baseline.[5]

Baseline enterprise budgets in the ASM were modified to reflect changes in forage production. Changes in forage production/availability in each region would be expected to affect the livestock production budgets by changing (1) the acres of grazable forage required per animal per year; (2) the amounts of non-grazed feeds required per year; (3) the amount of salable product produced per animal per year, or (4) some combination of all of these.

In addition to climate-induced changes in forage production, modifications were also made to reflect the direct effects of climate on livestock (cattle) production and costs were estimated. These include the effects of elevated summer temperatures on intake of forage and supplemental feeds (appetite depressing) and, secondarily and decreased energy requirements for body maintenance due to warmer winters.[6] In all cases the negative effects of hotter weather in the summer would be expected to outweigh the positive effects of warmer winters. Based on this analysis, adjustments were made in estimates of primary production to reflect the effect of temperature change on livestock performance.

Procedures and Results

The scenarios evaluated with ASM include: (1) two baseline configurations of ASM (1990 economic and agronomic conditions; 2060 economic and agronomic conditions); (2) two uniform temperature-precipitation-CO_2 combinations for both 1990 and 2060 ASM base models; (3) a series of sensitivity analyses exploring producer adaptation (mitigation) options based on the projected adjustment possibilities discussed above and changes in exports based on changes in world food production obtained from Rosenzweig and Parry (1993); and (4) two GCM-based climate forecast scenarios (GISS and GFDL-R30). Results from these general categories of scenarios (base models, combinations of climate changes, sensitivity analyses, GCM-based analyses) are summarized in this section.

Base Case(s)

The base case(s) solution to ASM is important because the economic consequences of climate change are measured as changes from the base case values. Specifically, the optimal objective function value from ASM represents the maximum social welfare (the sum of consumers and producers surpluses) for a given configuration of the model.

Previous analyses using ASM measured the consequences of climate change relative to 1990 base values. Although climate change may not occur for decades or longer, the use of 1990 conditions has merit because forecasting changes in income, prices and other economic phenomenon decades into the future is likely to introduce more uncertainty into the analysis than that introduced by the forecast changes in yields. However, because of these economic forces, the agricultural sector on which any climate change will be imposed is likely to be dramatically different from 1990's agriculture. Thus, in this assessment, we explore the difference in economic consequences between both 1990 conditions and possible economic conditions in 2060 (the time at which some analysts believe an effective doubling of CO_2 will occur). While the 2060 ASM base is speculative, at best, comparisons of climate change consequences measured against a 1990 base case and a 2060 base case can provide insight as to the importance of the time horizon used in such assessments.

The base cases are used as benchmarks against which to measure the economic consequences of each climate change analysis. The validity of the 1990 agronomic and economic conditions base model (the objective function value) is linked to the accuracy of the endogenous prices and quantities under 1990 conditions. The modeled and actual 1990 prices and quantities have been shown to be quite similar (Chang et al 1992), indicating that ASM provides a reasonable approximation to 1990 conditions and associated welfare. The 2060 base solution reflects changes in yields (reflecting technological change), demands and resource availability projected over the 70 year period (from 1990); the solution represents maximum welfare under these conditions. It is not possible to validate the welfare values for the 2060 ASM.

There is a measure of social welfare (objective function value) associated with each climate change analysis (uniform and GCM) performed with ASM, for both 1990 and 2060. The ASM welfare estimates for each scenario are evaluated against the appropriate base model. In discussing results we focus on changes in welfare, including consumers (both foreign and domestic) and producers surplus, along with indices of national price and quantity movements.[7] We also report changes in crop production by major production areas. Changes in regional crop production can provide important insight regarding shifts in crop market shares.

The two specific uniform climate change cases that are explored in detail are also used to conduct the sensitivity analyses. Table 1 describes these "central case" scenarios on which we focus. The key results or findings reported here thus pertain to (1) comparisons of these two climate cases (e.g., 2.5EC temperature and 7% precipitation increases, 530 ppm CO_2 level and 5.0EC temperature and 0% precipitation increase, 530 ppm CO_2 level); and (2) the sensitivity of these cases to alternative degrees of producer adaptations and to changes in U.S. exports arising from changes in world agricultural production. We focus on social welfare, resource use and regional production effects of these two cases.

Table 1. ASM analysis of climate change: specific scenario descriptions

Scenario number	Scenario description
	Primary analyses
1	Benign case (2.5EC temperature increase, 7% precipitation increase, 530 ppm CO_2), 1990 ASM
2	Adverse case: (5EC temperature increase, 0% change in precipitation, 530 ppm CO_2), 1990 ASM
3	Benign case: 2060 ASM
4	Adverse case: 2060 ASM
	Sensitivity analyses: adaptations and migration
5	Benign case: (1990) with adaptation
6	Adverse case: (1990) with adaptation
7	Benign case: (2060) with adaptation
8	Adverse case: (2060) with adaptation
	Sensitivity analyses: exports
9	Central (benign) case (1990) with GISS exports
10	Central (benign) case (1990) with GFDL exports
11	Central (benign) case (1990) with UKMO exports
12	Central (adverse) case (1990) with GISS exports
13	Central (adverse) case (1990) with GFDL exports
14	Central (adverse) case (1990) with UKMO exports
	GCM-based analyses
17	GISS climate forecast (1990)
18	GFDL-R30 climate forecast (1990)
19	GISS climate forecast (2060)
20	GFDL-R30 climate forecast (2060)

Welfare Changes

Table 2 contains the changes in welfare, by component, between the 1990 and 2060 ASM bases and the two case climate scenarios for 1990 and 2060. Each change is measured against the appropriate base case.

Table 2. Changes in welfare from base in 1990 $ (billions)

Climate change/ scenario number	Consumers surplus	Producers surplus	Foreign surplus	Total surplus
1990 central (benign) case (1)	9.67	1.64	3.55	14.86
	(0.86)[a]	(6.36)	(3.74)	(1.19)
1990 central (adverse) case (2)	-10.89	5.82	-2.18	-7.24
	(-0.97)	(22.60)	(-2.29)	(-0.58)
2060 central (benign) case (3)	47.66	-6.24	6.02	47.44
	(2.93)	(-16.31)	(6.35)	(2.70)
2060 central (adverse) case (4)	-11.40	20.89	-9.33	0.15
	(-0.70)	(54.61)	(-9.85)	(0.01)

[a] percentage change in welfare from the base

The results reported in Table 2 are generally as expected. Specifically, the benign climate scenario (2.5EC, +7% precipitation, 530 ppm CO_2) results in a net welfare gain of approximately $15 billion per year for the 1990 model and a gain of $47 billion under 2060 conditions (both estimates are in 1990 dollars). The larger gain under 2060 conditions reflects the generally higher level of economic activity assumed for 2060 (higher per capita income and population, greater commodity demand, higher yields). The welfare changes under the harsher climate (5.0EC, 0% precipitation, 530 ppm CO_2) translates into a welfare loss of $7 billion under 1990 conditions and a small welfare gain ($0.15 billion) under 2060 conditions. For perspective, these welfare changes are small percentage changes relative to the total base value (less than 3 percent for the largest change recorded here). Thus, the overall effects of climate change, when viewed in terms of the total value of consumers and producers surplus for the agricultural sector, are very modest. Changes in specific components of total welfare are somewhat higher, particularly for changes in producers welfare.

A different perspective can be gained by comparing these welfare changes arising from the incremental climate changes to previous estimates of climate change effects on agriculture. The results of

Adams et al. (1990, 1995) are a useful point of reference, given the use of ASM in each of these earlier studies. Despite the use of the same modeling procedure, there are differences that prevent a strict comparison. The major difference is that these two earlier studies use GCM-based yield forecasts which do not compare with any of the uniform incremental changes estimated here. Perhaps the closest comparison is between the UKMO-based results reported in Adams et al. (1993a) for 1990 conditions and the adverse central case study. Under the UKMO scenario, Adams et al. estimated an overall loss of $18 billion. The present study shows lower losses ($7 billion) than obtained under UKMO. The $11 billion difference can be attributed to the changes in ASM in the present study as well as to differences in the climate change scenarios. The source of the differences in economic effects is explored more thoroughly in the results from the two GCM-based analyses reported subsequently.

Changes in Regional Production Patterns

Climate change is expected to change agricultural production patterns. Previous agronomic studies suggest that global warming will have both positive and negative effects on production. Crop production may be enhanced in cooler areas, as warming reduces climate barriers to production. Conversely, some areas may become too warm for production of current crops. Unless heat-tolerant crops are available, such regions will see a decline in agricultural output.

An important feature are changes in national and regional crop production under each analysis. At the regional level, changes in crop production indicate possible changes in comparative advantage. Table 3 reports changes in crop production under the four central case scenarios. Specifically, the table provides index numbers of total crop production for the 10 major production regions in ASM. These index numbers are measured against the appropriate base-level production (base production equals 100).

Table 3. Regional index numbers for crop production

U.S. region	1990 central (benign) case (1)	1990 central (adverse) case (2)	2060 central (benign) case (3)	2060 central (adverse) case (4)
Northeast	112.87	112.73	44.59	83.49
Lake States	163.79	94.68	165.91	122.66
Corn Belt	124.98	73.53	106.28	82.99
Northern Plains	152.77	143.15	113.54	148.75
Appalachia	103.74	77.02	96.48	59.02
Southeast	110.67	74.63	138.65	98.26
Delta States	78.71	71.32	91.30	70.68
Southern Plains	83.40	66.37	75.17	59.00
Mountain States	127.33	129.24	121.97	115.75
Pacific Coast	138.52	144.90	134.64	129.76

The results reported in Table 3 are similar to earlier findings in Adams et al. (1990, 1993a). That is, a general pattern observed in the four case studies is an expansion in more northerly agricultural regions of the U.S., with a corresponding decline in the southern latitude regions. For example, in the more favorable 1990 central case (scenario 1) all regions experience expansions in total crop production except the Southern Plains and Delta States regions. In the more negative case (scenario 2), gains are confined to the Northeast, Northern Plains, Mountain States and Pacific Coast, with losses observed at southern latitude regions. The same pattern holds for the 2060 results under both scenarios.

One difference between the present results on regional productivity and those reported in Adams et al. (1993a) concerns the southeast. In these earlier studies, the southeast experienced large reductions in crop production under all GCM scenarios. In the current analysis, the southeast actually increases crop production under the more favorable case scenarios (for both 1990 and 2060). Under the more negative case, the southeast experiences slight to moderate reductions, but these are smaller than in the earlier assessment.

This difference is due in part to the addition of heat-tolerant crops (citrus, tomatoes) to the southeast crop mix, which mitigate or offset the negative effects of temperature increases on crops such as soybeans and corn.[7] The migration possibilities, particularly along the northern zones of these southern regions, enhances the introduction of heat-tolerant crops. An implication of this finding is the importance of including a reasonable range of alternative crop options in agricultural assessments.

Role of Farmer Adaptations and Export Assumptions

Two key areas of uncertainty in assessing the economic consequences of climate change on U.S. agriculture are (1) the ability of farmers to adapt to long term changes in climate and (2) the effect on U.S. agriculture of changes in global food production and demand due to climate change. In terms of adaptation, historical evidence suggests that U.S. farmers readily adopt new technology; they also adapt rapidly to institutional and other changes. Evidence from the explorations of cross sectional data reported earlier suggest that farmers also adapt to climatic variations. However, the level of adaptation across large temperature changes has not been documented in the current record and remains a source of uncertainty.

Changes in world food production under climate change will influence U.S. agriculture, given the large share of some U.S. commodities that enter world markets. Assumptions regarding export demand elasticities in ASM have a impact on total welfare. Thus, the link between changes in world agricultural production and the welfare estimates obtained here requires exploration. Given the potential importance of these two factors in determining welfare estimates generated by ASM, a series of sensitivity analyses are performed here.

Role of Farmer Adaptations

To explore the role of adaptation possibilities in mitigating yield effects of climate change, yield changes generated by the plant simulation modeling approach were compared with those reported by the duality yield equations which reflect producer responses to present temperature and precipitation gradients. Based on the combination of results from the duality study, the effects of adaptations from the crop simulation models and the evidence regarding partial factor productivity, the magnitude of potential adaptations (mitigation) were estimated to be 50 percent for the benign central case and 25 percent for the adverse case. To test the potential effect of these adaptations, yields in ASM were adjusted from the levels that underlie the results reported above. The results of this sensitivity analysis are reported in Table 4.

Table 4. Sensitivity results: welfare changes under potential farmer adaptation in 1990 $ (billions)

Climate change/ scenario number	Consumer surplus	Producers surplus	Foreign surplus	Total surplus
1990 central (benign) case (5)	9.47	1.98	3.45	14.91
	(0.84)[a]	(7.85)	(3.64)	(1.20)
1990 central (adverse) case (6)	-7.76	4.19	-1.26	-4.83
	(-0.69)	(16.58)	(-1.32)	(-0.39)
2060 central (benign) case (7)	48.94	-6.72	5.84	48.06
	(3.01)	(-17.56)	(6.16)	(2.73)
2060 central (adverse) case (8)	0.39	13.18	-6.23	7.34
	(0.02)	(34.47)	(-6.58)	(0.42)

[a] percentage change in welfare from base

The changes in welfare measured for these alternative specifications of the two case scenarios are generally consistent with the magnitude of the difference in yield adjustments (of 50 and 25 percent). Specifically, the loss in welfare under the adverse case for 1990 has been reduced from over $7 billion to less than $5 billion under the new yield effects. Similarly, the adverse case for 2060 now shows a net gain of over $7 billion, compared with a $0.15 billion gain in the absence of these adaptation adjustments. For the 1990 and 2060 benign case analyses, the role of adaptations is less important (both show very slight gains with adaptations). The reason for this small effect on the benign case results is that under the adaptation runs only negative yield changes are modified in ASM. There are far fewer negative yield changes in the benign cases than in the adverse cases.

The significance of these findings is that assumptions regarding farmer adaptations and technological change play a role in the welfare effects estimated from ASM. Assessment of whether the adjustments used here are "reasonable" or plausible under future climate change is beyond the scope of this effort. However, future assessments need to explore the potential for farmer adaptations, along with the larger issue of the role of technological change.

Role of Exports Assumptions on Welfare Estimates

The U.S. is a major exporter of feed grains and other agricultural commodities. For some domestically produced crops, over 50 percent of production is exported. Given the importance of world supply and demand conditions in determining U.S. exports, an ideal assessment of the effects of climate change on U.S. agriculture should reflect concomitant changes in world food production. Such an effort would require analyses of global supply responses under climate change, an effort far beyond the scope of this project. Thus, the analyses reported above use import/export demand relationships (elasticities) based on historical levels.

We test the effect of global changes in agricultural production on the welfare effects of the central cases for the 1990 model by using recent estimates of changes in agricultural trade patterns under climate change (Rosenzweig and Parry, 1993). These estimates predict that climate change will alter the demand for U.S. exports of selected crops, with increases under GISS and mixed effects under the other GCMs. The estimates are tied to GCM forecasts and thus are not strictly comparable to the uniform scenarios used here. (The average temperature increases in GISS, GFDL and UKMO are 4.0EC, 4.2EC and 5.0EC, respectively.) Nonetheless, the directions of the changes are comparable. Given that none of the GCM's maps exactly to the uniform temperature and precipitation changes evaluated, we use results from each GCM in this sensitivity analysis. Specifically, the changes in U.S. exports for each GCM, by commodity group, are used to adjust export demands in the ASM. After calibration to insure internal consistency in prices and quantities, ASM is resolved for the four central cases. The use of three GCM's results in a total of 12 ASM solutions. The welfare changes for each of these sensitivity analyses are reported in Table 5.

The effect of changes in U.S. exports is to increase the welfare gains, or reduce the welfare losses, from each of the central case analyses. For example, 1990 welfare under the benign case increases from $14.7 billion to $15.6 billion (GFDL), $17.2 billion (GISS) and $43.9 billion (UKMO). Similarly, losses observed under the adverse case (of $7.2 billion) are now reduced dramatically or even reversed (to a gain of $26 billion under UKMO). The bulk of these gains are to producers and foreign consumers; the impacts on U.S. consumers is slight (due to the excess demand characteristic of agricultural exports).

Table 5. Exports results: changes in welfare from base in 1990 $ (billions)

Climate change scenario	Consumer surplus	Producers surplus	Foreign surplus	Net welfare
1990 GISS	9.02 (0.80)	2.32 (9.29)	5.81 (6.12)	17.15 (1.38)
1990 GISS	8.87 (0.79)[a]	2.42 (9.57)	4.35 (4.57)	15.64 (1.26)
1990 UKMO	9.11 (0.81)	2.67 (10.57)	32.13 (33.83)	43.91 (3.53)
1990 GISS	-5.45 (-0.48)	4.22 (16.72)	1.01 (1.14)	-0.15 (-0.01)
1990 GFDL	-4.96 (-0.44)	3.73 (14.75)	-0.02 (-0.02)	-1.25 (-0.10)
1990 UKMO	-5.41 (-0.48)	4.53 (17.92)	26.99 (28.41)	26.11 (2.10)

[a] percentage change in welfare from the base

GCM-based Climate Effects

The changes in economic welfare for the GCM-based analyses are reported in Table 6. These results reflect crop yield changes across regions arising from the regional temperature and precipitation changes forecast by the GISS and GFDL-R30 general circulation models. Unlike the uniform climate change scenarios, large differences in temperature and precipitation exist across regions, particularly with GFDL-R30 forecasts. These GCM-based results can thus provide insights into the potential importance of these regional differences in terms of national level economic consequences.

The changes in welfare associated with the GISS forecast is approximately $12 billion (measured against the 1990 base). This is 20 percent higher than the GISS welfare change reported in Adams et al. (1995). This 20 percent increase in welfare is due to the modification in ASM performed in the current assessment. Specifically, the inclusion of more crops and additional adaptation options, such as crop migration, allows the agricultural sector to more fully exploit the generally beneficial regional climatic condition forecast by GISS. Under 2060 conditions, the welfare change increases dramatically, to over $100 billion. Adams et al. (1995) did not perform a similar dynamic updating, hence no comparison is possible. However, the increase in welfare between 1990 and 2060 is consistent with increases observed under some of the more benign uniform climatic change scenarios reported earlier.

Table 6. Changes in welfare from base in 1990 $ (billion)

Climate change	Consumers surplus	Producers surplus	Foreign surplus	Total surplus
1990 GISS (21)	10.39	-1.89	3.46	11.96
1990 GFDL-R30 (22)	-20.39	9.40	-5.19	-16.18
2060 GISS (23)	20.58	45.43	50.63	116.64
2060 GFDL-R-30 (24)	-65.70	52.18	-3.35	-16.86

The GFDL-R30 analysis has no counterpart in the extant economic assessment literature (e.g., Adams et al. used an earlier GFDL run, QFLUX). As a result, it is not possible to assess how modifications in ASM affect economic estimates in this case. The large temperature increases in some important crop production areas (e.g., the Corn Belt) translate into large reductions in yields. Thus, this GCM is perhaps more closely parallels the yield reductions underlying the UKMO results in Adams et al. (1995) than those associated with GFDL-QFLUX. The loss, of approximately $15 billion, is slightly less than UKMO reported in Adams et al. (of $17 billion). This loss is also comparable to some of the losses reported for the most adverse temperature-precipitation-CO_2 combinations tested earlier.

The economic "response functions" developed with the 64 climate combinations are used to predict changes in economic welfare resulting from changes in temperature, precipitation and CO_2 levels. The GCM-based analyses provide a vehicle by which to test the "reasonableness" of those economic response functions predictions. Specifically, we use annual mean U.S. temperature and precipitation values from the GCMs in the response function to predict changes in welfare and then compare these changes in welfare with welfare changes obtained directly from the GCM analysis (Table 7). In this comparison, both GISS and GFDL-R30 were evaluated using both linear and quadratic response functions.

For GISS, the increase in welfare predicted by the 1990 linear response function is $2.3 billion; for the quadratic, the change in welfare is $3.1 billion. Thus, in this case, the direction of effect reported by the uniform climate change assumption is similar (positive) but the change is about a fourth of the value estimated from the actual ASM solution reported in Table __. For 2060, the linear predicts a gain of $13.2 billion while the quadratic result in a gain of $86 billion. The quadratic is close to the $116 billion reported in Table 8, while the linear response function substantially under predicts the change in welfare. For GFDL-R30, the response function predictions differ dramatically from those in Table 8. In three of the four cases (1990 quadratic, 2060 linear and quadratic), the signs are reversed, e.g., where the ASM solutions in Table 8 report losses (of $15 billion), gains of from $1 to $80 billion are predicated. One reason for this is that the response functions are based on uniform changes across all regions, whereas the GFDL-R30 GCM forecast dramatically different changes in temperature across regions. For example, under the GCM forecasts, the Corn Belt is forecast to experience nearly a 5EC increase in temperature, which results in large reductions in yields of two important crops (corn and soybeans). However, the average or uniform warming is a more modest 4.4EC (similar to GISS). These findings suggest the potential importance of regional differences in climate; care should thus be used in performing economic assessments when applying uniform changes (or the associated response functions) if climate change is expected to translate into non-uniform changes in temperature and precipitation.

Summary and Conclusions

The purpose of this paper is to investigate whether some of the acknowledged limitations found in existing studies of climate change and agriculture "matter." In particular, this study extends previous work by (1) incorporating climate sensitivity for other paricularily more heat tolerant crops found in the southern U.S.; (2) considering the impacts of farmer adaptations to climate change; (3) allowing for crop migration into regions where those crops are not currently being grown; (4) incorporating changes in forage production and livestock performance; and (5) assessing the potential for technological change, as manifested in present and future yields, to offset climate change.

This assessment also investigates the influence of climate scenarios on economic estimates. Specifically, we use both uniform incremental climate change scenarios and GCM forecasts. The scenarios include 16 combinations of alternative temperature and precipitation changes (0, 1.5EC, 2.5EC, and 5.0EC for temperature; and -10%, 0%, 7%, and 15% for precipitation). In addition, we considered four alternative levels for atmospheric CO_2 concentrations (355, 440, 530, and 600 ppm). Each of these 64 scenarios is evaluated here for both 1990 and 2060 conditions; together, they comprise the data set for the estimation of a climate change "response function" for 1990 and 2060 conditions. The two GCM-based analyses were performed using climate forecasts from the GISS and GFDL-R30 general circulation models. These GCM-based analyses provide a point of comparison with previous studies as well as a test of the reasonableness of the economic effect "response functions" developed from the 64 uniform scenarios.

The uniform change assessment features two "central case" scenarios to illustrate in detail the range of economic effects arising from climate change; a benign (and perhaps optimistic) case and a more negative or adverse climate case. The first case assumes a uniform incremental temperature change of 2.5o, a 7% precipitation change, and a 530 ppm atmospheric CO_2 concentration. The more negative case is a uniform incremental change of 5.0EC in temperature with no change in precipitation and an atmospheric CO_2 concentration of 530 ppm. These two "case studies" are also used in a series of sensitivity analyses concerning the role of farmer adaptations and export (world food production) assumptions.

The analyses of the various climate change scenarios reveals a range of potential economic effects on the welfare of consumers and producers. The magnitude of the welfare losses and gains from this wide range of temperature, precipitation and CO_2 combinations varies. In general, increases in precipitation and CO_2 increase welfare. Under the quadratic functional form, slight to modest increases in temperature can also increase welfare. The response function analyses also show that increases in CO_2 and precipitation can offset the potentially negative effects of large temperature increases.

The magnitude of welfare changes, by welfare component, are examined in a set of central case analyses. For the optimistic case, welfare gains of $14.7 and $46 billion are predicted for 1990 and 2060, respectively. The adverse case shows a loss of $7.4 billion for 1990 and a gain of $0.15 billion for 2060. These values are small percentage changes in total agriculture value (less than 3 percent of the value of the base model solution). Thus, in the aggregate, climate change appears to be a relatively small stress to agriculture. The welfare losses from adverse climate change also tend to be smaller than previous estimates, while the gains from favorable climate change tend to be larger. This is due to the more comprehensive treatment of adjustment possibilities such as the inclusion of new crops and migration possibilities, in this analysis. As noted in earlier studies, climate change of the type evaluated here is not a food security issue for the U.S.

Sensitivity analyses, based on historical evidence regarding farmers' behavior, indicated that potential farmer adaptations to climate change can play a role in mitigating adverse effects of climate change. This finding, coupled with the importance of technology and related assumptions underlying the 2060 analyses, supports inclusion of such features in future economic assessments. Sensitivity analyses on export assumptions reinforces the importance of world trade (exports) on the welfare of the U.S. agricultural sector. Global climate change is likely to increase the demand for U.S. commodities, with possible increases in welfare. These increases result in a net gain in welfare for most case studies evaluated here.

The GCM-based analyses indicate that if climate changes according to the GISS forecasts, net welfare increases by $12 billion for the 1990 base. This value is approximately 20 percent greater than the previous analyses of GISS climate change using ASM (Adams et al. (1995). The difference (increase) is due to changes in ASM, such as addition of crops and other mitigation opportunities, which allow the agricultural sector to more fully exploit the new climate conditions. The GFDL-R30 analyses reveals losses of over $14 billion (measured against the 1990 base). These losses arise from the harsher climate conditions under the GCM. Results from the GCMs do not compare well with estimates generated by the response functions (derived from the 64 uniform change scenarios). This finding suggests that regional differences in climate are potentially important determinants of estimates of national economic consequences.

The results generated in the analyses performed in this project provide another set of estimates of the economic effects of climate change on agriculture. The study addresses some problems found in earlier studies, but also suffers from some similar shortcomings arising from the long run nature of the problem. However, by including a larger number of crops and livestock activities and adaptation possibilities than used in previous climate change assessments, this current study represents the most comprehensive study to date of the effects of climate change on U.S. agriculture.

Endnotes

2. The r_1 terms have been estimated by using 40 years of agricultural statistics to determine the annual percentage rate at which those items have increased over time. The model takes the base yield starting in 1990 and the elapsed time to the desired year and then multiplies the base number by the $(1 + r_1)^{t\text{-}base}$ to obtain the updated estimates.

3. Climate change can also affect the demand for water in the model. Changes in water demand are estimated for both dryland and irrigated crops using the plant simulation models. Water supplies are also altered (from 1988-92 levels) in these analyses.

4. This second approach, in its reliance on cross-sectional yield and climate data for the midwest, generates results concerning effects on producers profits which can be compared with those estimated recently by Mendelsohn, et al.

5. Information on these effects was obtained by Dr. Jerry Stuth, Range Animal Nutrition and Grazing Specialist in the Department of Rangeland Ecology and Management at Texas A&M University.

5. In developing estimates of forage production changes for the regions in ASM, consideration was given to the number of cattle in each region, and their relative proximity to each of the sites for which forage production was simulated. Weights were then assigned for each of the sites relative to the proportion which its production would contribute to the estimated average production for each region.

6. In this study, we address changes in natural resource use, including changes in land (irrigated and dryland) and water use at the national level. These are not reported here due to space limitations.

7. A second factor is that the previous studies use GCM climate forecasts, which are, on average, warmer than the benign central case conditions. However, the more adverse case here is actually warmer (5EC) than the GISS (4.2EC) and GFDL (4.4EC) average global temperature forecasts.

Thus, the uniform increases used here are likely to be less important in explaining the findings for the southeast than is the addition of heat-tolerant crops to ASM.