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The Uncertainty due to Spatial Scale of Climate Scenarios in Integrated Assessments: An Example from U.S. Agriculture*

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ABSTRACT

We investigate the effects of different climate scenario resolutions on estimates of the impacts of future climate change on agriculture in the United States. Climate scenarios were developed using both a coarse resolution, global scale general circulation model and a spatially more refined regional climate model, nested within the coarse model. The scenarios are similar on a very broad regional scale, but show important differences on a subregional scale. In most areas the fine scale scenario produces a more severe climate change. Simulated changes in crop yields (e.g., cotton, soybean, corn, wheat) were constructed under both the coarse and fine scale scenarios for the conterminous United States. The results demonstrate that the spatial scale of climate scenarios affects the estimates of regional changes in crop yields on several levels of spatial aggregation and the economic impact on the agricultural sector as a whole. For the elevated CO_2 case, national economic welfare increased under the coarse scale climate scenario, but remained virtually unchanged under the fine scale scenario. With adaptations, both scenarios showed substantial increases, but these were still considerably larger for the coarse scale scenario. Regional indicators of economic activity were of opposite sign in some regions, based on the scenario scale for both cases. Such differences in economic magnitudes or signs become important in public policy debates concerning climate change. Hence refinement of spatial scale of scenarios should be carefully considered in future regional integrated assessments.

Keywords: climate scenarios, spatial scale, agricultural impacts, uncertainty.

1. INTRODUCTION

The coarse spatial scale of climate scenarios generated from general circulation models (GCMs), which is on the order of hundreds of kilometers, has long been a concern of climate change impacts researchers [1, 2], because of the perceived mismatch of scale of the climate change information compared to the fine resolution or even site specific scale of information required by most impacts models, such as crop and hydrological models [3, 4]. There are now techniques available (e.g., regional climate modeling and statistical downscaling) for generating high resolution (10 s of kilometers) climate change scenarios [5–7], but the regionalization or downscaling[6] adds another element of uncertainty to the cascade of uncertainties attending climate change impacts research and regional integrated assessments [8, 9].

Uncertainties in future greenhouse gas emissions and the differential responses of climate models are two of the major uncertainties in determining future climate and its impacts [8, 10]. It is also known, however, that regional climate models, which provide much needed regional detail of climate, often simulate changes in climate that are significantly different from those of the coarse resolution global climate model within which the regional model is embedded [11]. The basic strategy in nested regional modeling is to rely on the global model to simulate the response of the global circulation to large scale forcings of climate, and the regional model to account for the higher resolution forcings (e.g., complex topography) as well as to enhance the simulation of climate variables at fine spatial scales.

While a number of impact studies have employed high resolution scenarios [8] few have indicated whether downscaling results in important differences in calculations of assessment results compared to those calculated using scenarios from the coarse resolution climate model, and none have examined the effects on national economics.

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[6]In this article we use the terms 'regionalization' and 'downscaling' to refer to the production of high resolution climate scenarios from coarse resolution global climate model information. Regionalization is the term used in the Intergovernmental Panel on Climate Change (IPCC), Third Assessment Report, but downscaling is a more generic term often used in the literature.

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There have now been a handful of studies in agriculture wherein these comparisons have been made [12, 13] for crop yields.

The overarching goal of this research is to examine the sensitivity of United States national and regional economic effects to changes in simulated crop yields elicited from climate scenarios developed from high and low spatial resolution climate models. In this regard, the project is a modeling study that combines climate scenarios, crop models, and an agricultural economic model to explore the central research question posed above. Scenarios of different scale provide climate input to a series of crop models, which produce estimates of the effect of the climate change on agriculture in the United States on two different spatial scales. These simulated crop yield contrasts are then used as input to an agriculture sector model that produces the national and regional economic effects also on two different spatial scales.

2. CLIMATE SCENARIOS

The high resolution climate scenarios used here were generated from three sets of regional simulations with the regional climate model RegCM2 [14, 15], (henceforth referred to as RegCM) run at a 50 km grid point spacing nested in 5 years of control and 5 years of doubled CO_2 runs of the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) GCM [16], with a horizontal spatial resolution of about 400 km (i.e. 5° in physical space).

The CSIRO Mark 2 GCM is coupled to a 50 m depth mixed layer ocean. Typical parameterizations in the model include those for the boundary surface layer, soil moisture, ice dynamics, and surface vegetation. The global mean increase in surface temperature in the doubled CO_2 experiment is 4.3 °C and the global increase in precipitation is about 10%. For further details on the model and the simulations used here see [16, 17].

The RegCM is an augmented version of the NCAR/Pennsylvania State University mesoscale model MM4. Parameterizations added for model use in climate studies include a complete surface package [18], an explicit boundary layer formulation [19], a mass flux cumulus parameterization [20], and a simplified explicit moisture scheme [21].

The RegCM simulations included one for the western 2/3 of the conterminous United States [22, 23], one for the Great Lakes region [24, 25] and one for the Southeast [26, 27]. Climate changes in regions that overlapped in the runs were checked for comparability, and results from the runs whose lateral boundaries were furthest from the area of concern were usually used. The control and doubled CO_2 results from the five years of the CSIRO simulation formed the coarse scale scenario. In applying these results, it was assumed that changes in climate were uniform across each grid box of the coarse model.

The broad characteristics of the coarse and fine scale climate changes are similar, but important differences can be found on the subregional (50–100 km) scale, especially for precipitation [22]. We emphasize here contrasts in the climate changes in the major cropping regions of the U.S. Comparative scenarios for three of these regions are presented in Table 1. In the central Great Plains (e.g., Nebraska, Kansas, Iowa, Missouri), the RegCM tends to produce larger increases in temperature than does the CSIRO model in winter and fall, but also produces larger increases in precipitation in the key cropping months of June and July (Table 1) [22, 23]. In the southern Plains (Oklahoma, Texas) the climate change of the RegCM is less harsh than that of the CSIRO. In spring precipitation increases are seen in both models, but these tend to be larger in the RegCM. In summer, decreases predominate for both models, but the CSIRO experiences larger decreases.

Table 1. Changes in climate (CSIRO vs. RegCM) for three regions of the U.S.

	Central Great Plains[a]		South Great Lakes[b]		Southeast[c]	
	CSIRO	RegCM	CSIRO	RegCM	CSIRO	RegCM
Av. temp. change (°C)						
Winter	4.9	5.2	6.3	5.2	4.3	3.7
Spring	5.7	5.6	6.5	5.2	5.1	4.7
Summer	4.5	4.4	4.5	4.8	4.0	4.4
Fall	4.6	5.0	5.2	4.3	4.3	4.5
Precipitation % change						
Winter	9.4	10.8	−10.0	15.0	−18.9	−1.5
Spring	36.8	24.1	43.0	39.0	35.7	26.5
Summer	−1.0	6.2	−1.0	−15.2	−17.0	−30.9
Fall	12.8	14.3	16.3	25.4	−7.2	2.7

Note. [a]Kansas, Nebraska, Iowa, Missouri.
[b]Indiana, Illinois, Ohio.
[c]North Carolina, South Carolina, Georgia, Northern Florida, Alabama, Mississippi, Louisiana, Arkansas, Tennessee.

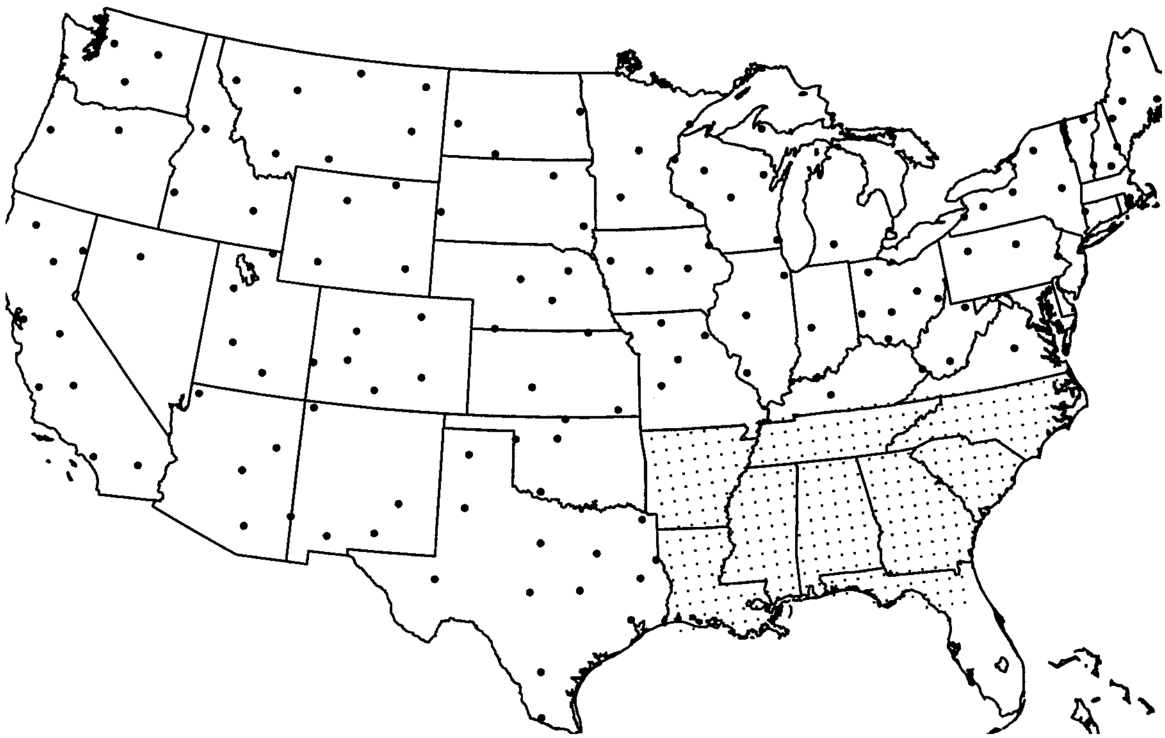

Fig. 1. Locations of climate stations (large dots) where crop models were run for areas of the United States outside of the Southeast, and the gridded climate stations used in the Southeast (small dots).

With regard to the Great Lakes region an important distinction in what the models can simulate needs to be mentioned. The CSIRO model has no representation of the Great Lakes, while the higher resolution RegCM model includes a fully coupled one-dimensional lake model [24]. For the area south of the Great Lakes (Illinois, Indiana, and Ohio, Table 1) the CSIRO produces a less deleterious climate change than does the RegCM. While both models produced increases in precipitation in early spring, the increases are larger in the CSIRO. In early to mid-summer, the CSIRO produces slight precipitation increases, but the RegCM produces a complex pattern of increases and decreases. In winter there is an opposite direction of change in precipitation for the two scenarios, but it has much less of an effect on crop yields than the contrasts in precipitation in the summer, a critical season for most crops. Temperature increases tend to be greater in the CSIRO by about 1 °C.

In the southeastern U.S.[7] both models simulate increases in precipitation in spring, and substantial decreases in summer, but the CSIRO produces larger increases and smaller decreases compared to the RegCM, particularly along the agriculturally productive Coastal Plain (Table 1). Temperature increases tend to be larger in the CSIRO, except in summer, when the maximum temperature increase in the RegCM is larger in conjunction with the greater soil drying with larger decreases in precipitation particularly along the coastal plain. The results for the RegCM naturally are always spatially more variable than those for the CSIRO model.

From these runs (CSIRO and RegCM) we formed two different resolutions of climate change scenarios. To form the coarse resolution scenario, the monthly mean climate differences ($2 \times CO_2 -$ control) or ratios ($2 \times CO_2/$control) for the relevant variables were applied to daily meteorological observations (1961–1985) on the 50 km grid scale. Variables included daily precipitation, maximum and minimum temperature, and incident solar radiation. The latter variable was stochastically generated. This baseline climate dataset included all 50 km grids in the southeastern U.S., but the baseline representation of the rest of the U.S. was coarser. Figure 1 shows the distribution of stations used for the Southeast and the other areas of the U.S. outside of the Southeast. This differential representation resulted from the fact that this project originated from a focus on the southeastern U.S. [26, 27]. We examined what effect the differential resolution of the base stations had on the final calculations of percent changes in crop yields for some crops (see Section 3) by using a coarser resolution of stations for states in the southeastern region and comparing these results with those using the denser coverage. Essentially, on the final levels of aggregation used by the economic model (state level, see Section 4) the percent changes in yields were very

[7]The Southeast U.S. regarding the climate descriptions refers to the large region including states listed in Table 1. In Section 4, the Southeast refers to only South Carolina, Alabama, Georgia and Florida.

similar (for both the regional climate scenario and global model scenario) regardless of the density of base stations. Hence, we determined that this differential treatment, while introducing some uncertainty in our analysis did not affect the overall tendency of our results. What is most important in this analysis is that the base conditions for the high and low resolution scenarios be identical. This condition is not affected by having a differential density of stations in different regions.

For the coarse resolution scenario, all 50 km grids represented by a climate site and encompassed by a given coarse resolution CSIRO grid would receive the same set of changes. The high resolution scenario was formed by applying the changes from the regional climate model to the same set of baseline observations, such that each 50 km grid received a unique set of changes.

3. APPLICATION TO CROP MODELS

We then used the observed gridded climate and the coarse and fine resolution scenarios to drive the CERES and CROPGRO version 3.1 family of crop models [28] as well as a cotton model, GOSSYM [29–31]. CERES/CROPGRO crops included corn, rice, sorghum, soybean, and wheat. Management to the crop model inputs, such as sowing dates, cultivars, and irrigation, were taken from various USDA agricultural extension bulletins and recommendations from extension agents. The State Soil Geographic (STATSGO) database [32] was used to determine the soil type and parameters for each represented 50 km grid. The best agricultural soil in the grid was chosen to represent the grid. Since we assumed no nitrogen stress in the runs, fertilizer applications were not used as an input.

We performed crop model runs for the base case (using observed climate and a CO_2 level of 330 ppm), for climate change plus an elevated CO_2 level, and for the latter plus adaptations. Both irrigated and dryland runs were produced where appropriate. For the climate change plus elevated CO_2 runs (referred to as the elevated CO_2 case), we assumed that the climate scenario was appropriate for the period around 2060, at which time the actual CO_2 level would reach 540 ppm, based on the assumption of the IS92a transient emissions scenario [33]. Adaptations included adjustments in planting dates and/or changes in cultivars. We note that our treatment of adaptations is relatively simplistic, and we do not consider in any depth the uncertainties in the regional details of future potential differences in adaptive capacity and vulnerability. Different adaptations minimize the negative effects of the regional climate change (or optimize yields), depending on the scale of the climate scenario. Changes in sowing date and variety were chosen to maximize yields. Carbone et al. [34] discusses how the adaptations for soybean differ based on the scale of the climate scenario in the Southeast.

We examined the response of the crop models at the state level by aggregating the 50 km grid results to state and higher regional levels of aggregation appropriate for the economic model (see Section 4). Table 2 summarizes crop yield changes for the two scenarios for these large regions of the U.S.

The scale of the climate scenarios resulted in substantial differences in percentage change in yield for most crops

Table 2. Percentage change in crop yields for some megaregions.

Region	Crop	Elevated CO_2				With adaptation			
		CSIRO		RegCM		CSIRO		RegCM	
		Dry.	Irr.	Dry.	Irr.	Dry.	Irr.	Dry.	Irr.
Corn Belt	Cotton	−2	37	−19	37	29	48	15	48
	Corn	−5	−20	−17	−18	5	−13	−9	−13
	Soybeans	33	39	−3	41	37	42	2	45
	SoftWW	−7	−8	−2	−2	−6	−7	−1	−1
	Sorghum	−4	−11	−19	−11	3	−11	−12	−10
	Rice	N/A	−6	N/A	−14	N/A	2	N/A	4
Northern Plains	Corn	14	−16	22	−14	27	−14	48	−8
	Soybeans	58	52	62	54	58	41	65	41
	HRSW	−19	−19	−13	−10	−1	−18	4	−9
	HRWW	3	−2	5	−6	6	−2	9	−5
	Sorghum	−9	3	4	3	1	4	11	4
Delta States	Cotton	−2	21	−9	19	24	31	15	28
	Corn	−2	−12	4	−9	9	−8	11	−6
	Soybeans	−37	24	−44	14	1	28	2	25
	SoftWW	−23	−24	−16	−18	−23	−24	−16	−18
	Sorghum	−37	−13	−35	−15	−21	−10	−20	−8
	Rice	N/A	−3	N/A	−7	N/A	1	N/A	6

(*continued*)

Table 2. (*continued*).

Region	Crop	Elevated CO_2				With adaptation			
		CSIRO		RegCM		CSIRO		RegCM	
		Dry.	Irr.	Dry.	Irr.	Dry.	Irr.	Dry.	Irr.
Southern Plains	Cotton	57	78	67	76	85	82	84	80
	Corn	13	−15	34	−13	60	−12	81	−12
	Soybeans	−38	8	6	8	51	14	51	8
	HRWW	−13	−10	7	−13	−8	−10	11	−13
	Sorghum	−3	−6	−11	−6	11	−3	5	−2
	Rice	N/A	0	N/A	1	N/A	8	N/A	14
Pacific	Cotton	N/A	−10	N/A	−10	N/A	−7	N/A	−7
	Corn	22	8	24	9	22	13	25	14
	HRSW	23	−19	48	−12	34	−18	82	−9
	HRWW	44	12	42	14	44	12	44	14
	Sorghum	47	39	8	38	47	48	8	46
	Rice	N/A	−25	N/A	−18	N/A	14	N/A	8
Lake States	Corn	3	−12	0	−9	9	−7	4	−4
	Soybeans	106	56	65	64	116	63	79	70
	HRSW	−20	−24	−20	−19	−4	−24	−3	−18
	HRWW	3	1	12	12	3	1	12	12
	SoftWW	20	12	30	45	22	13	35	46
South East	Cotton	20	35	3	32	36	43	21	40
	Corn	−3	−10	−1	−8	3	−6	7	−5
	Soybeans	−28	31	−69	19	−18	31	−35	20
	SoftWW	−24	−26	−22	−24	−23	−25	−21	−24
	Sorghum	−28	−7	−54	−10	−21	−7	−40	−5
Mountain States	Cotton	N/A	35	N/A	32	N/A	41	N/A	38
	Corn	10	−6	11	−14	20	0	40	−12
	HRSW	22	−19	48	−12	33	−18	81	−9
	HRWW	−18	41	−27	28	−16	42	−26	28
	Sorghum	10	57	18	59	10	89	19	93

Note. Pacific: Washington, Oregon, California.
Southern Plains: Texas, Oklahoma.
Northern Plains: North Dakota, South Dakota, Nebraska, Kansas.
Corn Belt: Iowa, Missouri, Illinois, Indiana, Ohio.
Delta States: Arkansas, Louisiana, Mississippi.
Lake States: Michigan, Minnesota, Wisconsin.
Mountain States: Montana, Idaho, Colorado, Utah, Nevada, New Mexico, Arizona.
South East: South Carolina, Alabama, Georgia, Florida.
HRWW = Hard Red Winter Wheat.
HRSW = Hard Red Spring Wheat.
SoftWW = Soft Winter Wheat.
Dry. = dryland; Irr. = irrigated; N/A = not applicable.

across the cases both on the state and regional scales. However, which scenario produced larger increases (or smaller decreases) in yield varied across the regions and sometimes with the crop (Table 2), especially for dryland production. For the most part, in the Corn Belt and Southeast, the main crops modeled fared better with the CSIRO scenario, but in the Northern and Southern Plains better results generally were obtained with the RegCM high resolution scenario. In many of the other regions, results depended on the particular crop. For example, in the Delta States, cotton and rice (irrigated only) suffered smaller losses or greater gains in yield with the coarse resolution scenario, but corn and wheat faired better with the high resolution scenario. Similar mixed results were found in the Lakes States, Mountain States, and the Pacific Coast States. On occasion, some crops in some regions exhibit opposite directions of change in yield based on the scenarios. For example, in the Corn Belt in the elevated CO_2 case, soybean yields increase substantially with the coarse scale scenario, but decrease slightly with the fine scale. In the Northern Plains, sorghum yields decrease with the coarse scenario but increase with the fine scenario.

As would be expected, results with adaptation almost always improve, and most changes in yield from the baseline become positive in most regions for most crops.

Occasionally this does not prove to be the case, however. For example, in the Delta States and the Southeast there is very little improvement in wheat with adaptation. In this instance neither moving the planting date nor introducing new cultivars improved the yields. More details on these wheat results can be found in Tsvetsinskaya et al. [35].

Among the crops across all regions, cotton fares the best under climate change regardless of the scenario. Large yield increases, particularly with adaptation, are seen in most cases and regions (Table 2).

Irrigated yields for many crops tend to result in small decreases even with adaptation, since the increased temperatures with climate change shorten the growing season, and thus reduce the time to accumulate dry matter. Of course irrigated baseline yields are considerably higher than dryland yields. Again, this does not tend to be the case with cotton since it benefits more than any other crop from higher temperatures in many areas, except in southern California. In both cases and for all crops, irrigated yields exhibited much smaller contrasts based on the scenario scale, since only contrasts in temperature change (and secondarily solar radiation) affect the yields.

On the finer level of aggregation, the state level, a greater range of contrasts are seen. An analysis of variance (ANOVA) was performed on the state-level simulated yields, separately for each crop. Five different cases, each with 25 years of yields were included: the base case, the two climate scenarios with elevated CO_2 and the two adaptation cases. Comparisons were made among all paired combinations. For most crops in most states, the CSIRO and RegCM simulated yields were found to be significantly different at the 0.05 level, for both the elevated CO_2 cases and the adaptation cases. Fewer of the adaptation yields were significantly different compared to the elevated CO_2 cases. Wheat in states of the Southeast U.S. exhibited the fewest significant differences.

In the elevated CO_2 case for dryland corn, many of the eastern southern states experienced yield decreases under both climate scenarios, but the Carolinas suffered larger decreases with the fine scale scenario (Fig. 2a, b). In the Corn Belt states of Illinois, Indiana, and Ohio, yields also generally decreased, but the decreases were significantly larger with the fine scale scenario. Contrasts in Iowa were less striking, with both scenarios producing relatively similar

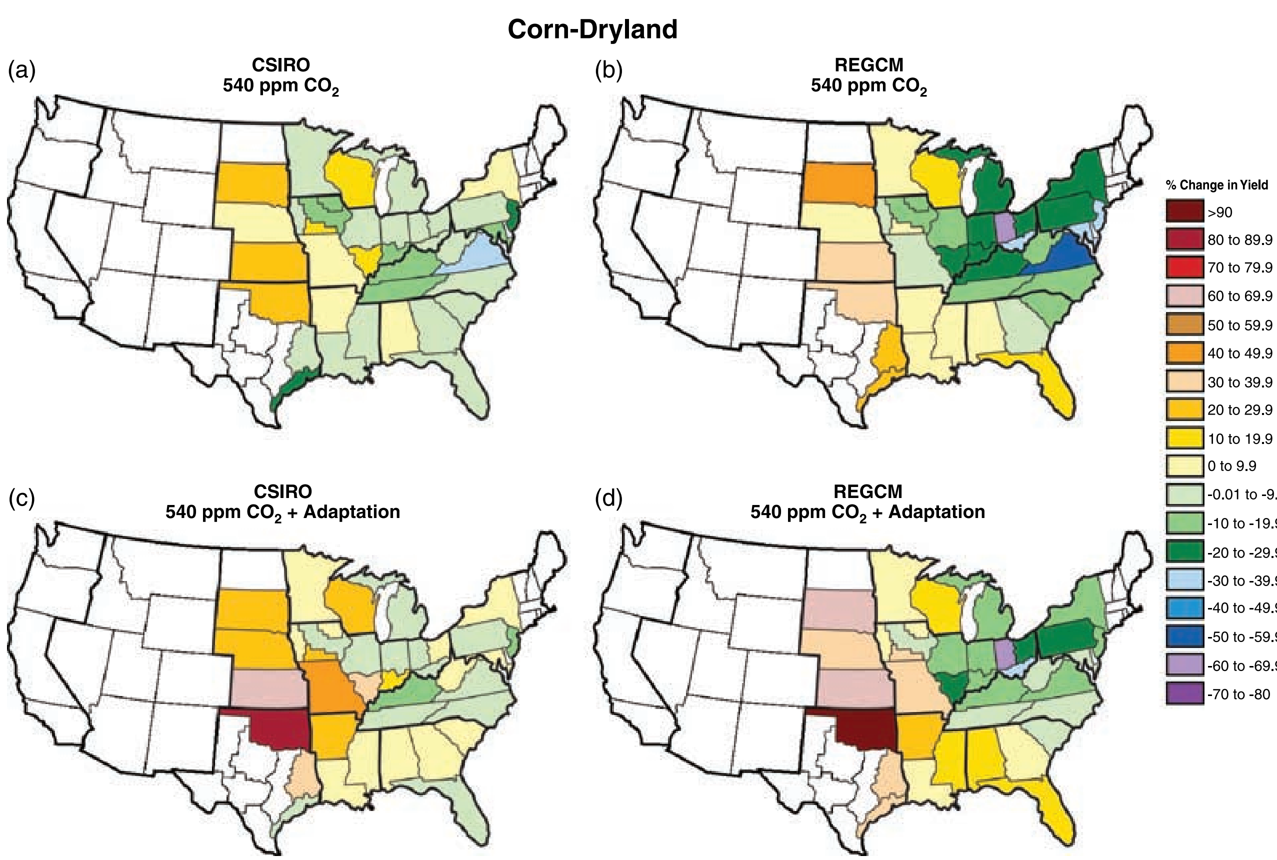

Fig. 2. Percentage change from base of dryland corn yields for the two climate scenarios and two climate change management cases: a. CSIRO (coarse scale) elevated CO_2, b. RegCM (fine scale) elevated CO_2, c. CSIRO (coarse scale) + adaptation, d. RegCM (fine scale) + adaptation. Units of analysis indicated are those used in the agricultural economic model, primarily states, except for sub-state units in Texas, and some midwest states.

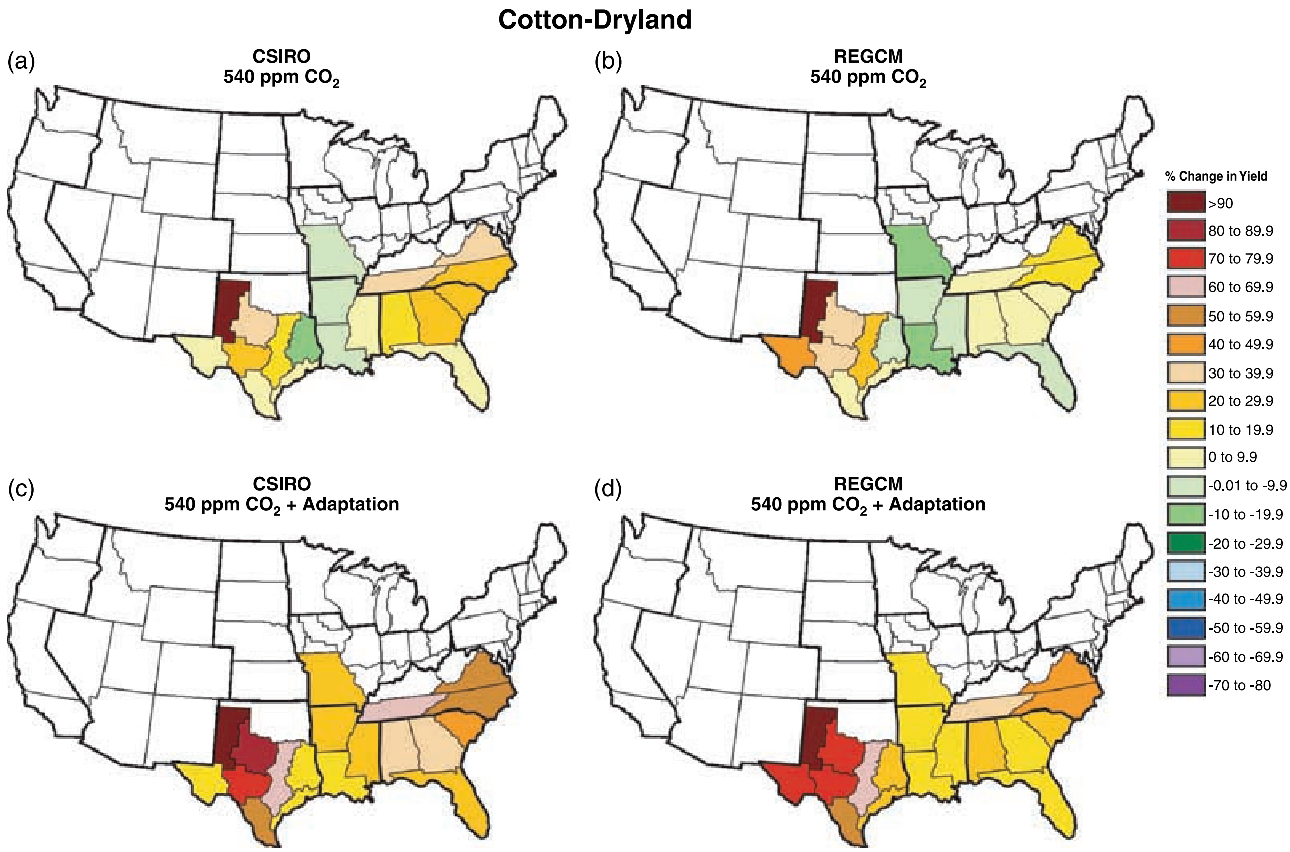

Fig. 3. Percentage change from base of dryland cotton yields for the two climate scenarios and two management cases: a. CSIRO (coarse scale) elevated CO_2, b. RegCM (coarse scale) elevated CO_2, c. CSIRO (coarse scale) adaptation, d. RegCM (fine scale) adaptation. Units of analysis indicated are those used in the agricultural economic model, primarily states, except for sub-state units in Texas, and some midwest states.

decreases in most of the state. Without adaptation we see primarily climate-related yield reductions. With adaptation, yields improved, but remained negative in the Corn Belt states. Since under adaptation yields are being optimized, contrasts in the yields between the scenarios tend to decrease (Fig. 2c, d), but the same qualitative contrasts are maintained.

As mentioned above, cotton faired better than most other crops. In the elevated CO_2 case (Fig. 3a, b), dryland yields generally increased in the eastern Southeast but they decreased in most Delta states (Mississippi, Arkansas, Louisiana) [36]. In the various sub-regions of Texas, yields increased. In the eastern Southeast, the coarse scenario yields increased much more than those of the fine scale scenario, whereas in Texas, the reverse was true. With adaptation, yields increased (over the base case) everywhere and the contrast between the effects of the two scenarios decreased (Fig. 3c, d), but the relative values remained as in the non-adaptation case.

These results for the changes in crop yields confirm the earlier results of Mearns et al. [12, 23] and Easterling et al. [37], who found significant contrasts in changes in corn and wheat yields with scenario spatial scale in the central plains. Here we have demonstrated this for the entire U.S. and for a greater variety of crops.

The causes for these differences in the effects of the climate scenario scale on crop yields are related to the different details of the climate changes and the complex physiological and plant/water interactions during each crop's growing season. Note, for example, in Table 2, that in the Northern Plains, different results are obtained for spring and winter wheat, since their growing seasons are quite different. Mearns et al. [12] give more detailed explanations for the Great Plains region for corn and wheat. Further explanations for crop yield results for the southeastern U.S. may be found in Doherty et al. [36], Tsvetsinskaya et al. [35], and Carbone et al. [34].

4. ECONOMIC MODELING

While changes in crop yield provide information on regional crop sensitivity, they do not give a measure of changes in aggregate crop production nor of the sensitivity of economic output at the national or regional level. For example, countervailing or offsetting sensitivity across regions, changes in crop mixes across regions and altered market prices allow a rebalancing of the initial crop yield effects. Consequently, it is important to derive information on the overall value of agriculture and examine its sensitivity to the contrasting results based on spatial scale. To do this, we used an economic model of the U.S. agricultural sector called the Agricultural Sector Model (ASM). ASM is a spatially disaggregate model that simulates the economic equilibrium that arises in the U.S. agricultural sector. It considers the regional impacts of yield changes, with endogenous price adjustments [38]. ASM represents production and consumption of primary agricultural products including both crop and livestock products. It has been used in many analyses of the interaction between agriculture and climate change [39–43].

Economic welfare in ASM is measured as the sum of consumers' and producers' surplus. These are monetary measures that represent, through supply and demand curves, the effects of changes in production and demand on producers' profits and consumers' (both domestic and foreign) expenditures.

The economic model contains 63 primary spatial units of analysis, which correspond to states in most cases except in the Midwest, Texas, and California, where sub-state units are delineated (these units are represented on Figs. 2 and 3). These units are aggregated into regions for some calculations. Such regional units are presented in Table 2. To evaluate the response of the U.S. agricultural sector we needed not only sensitivity information for the crops modeled, but also for the other crops, pasture, water availability and livestock production in the sector.

The changes in yields for these other crops (e.g., citrus, tomatoes, hay) and livestock commodities were determined via a proxy method based on other crop simulations for studies of agricultural crop yield change over the U.S. performed for the U.S. National Assessment [42, 43]. Since our focus here is on the sensitivity of the agricultural sector to climate scenario scale, we believe that the representative data from the National Assessment for these other items are acceptable.

No attempt was made to extrapolate changes in the economy out to the year 2060; the economic model assumes year-2000 economic conditions. Moreover, no changes in crop yields were assumed for countries outside the U.S. Previous agricultural sector studies indicated that the sector is not particularly sensitive to such international changes [44].

Percentage changes in crop yields and irrigation water use for all 63 primary spatial units of the ASM were produced, based on the two different climate change scenario resolutions for the elevated CO_2 and adaptation cases. In the experiments presented here only mean changes in yield were considered. In other experiments [45] the changes in the variability of these yields were also incorporated into a stochastic version of the ASM.

Table 3. Changes in welfare results in billion \$. The scenario/cases are: CSIRO: CSIRO (coarse) climate change + elevated CO_2; RegCM: RegCM (fine) climate change + elevated CO_2; CSIROA: CSIRO (coarse) + adaptation; RegCMA: RegCM (fine) + adaptation.

Scenario/case	Consumers	Producers	Foreign	Total welfare
CSIRO	5.96	−3.31	0.40	3.05
RegCM	3.47	−3.41	0.26	0.32
CSIROA	8.94	−3.87	0.62	5.69
RegCMA	7.76	−4.67	0.51	3.61

On a country-wide basis, both climate change scenarios for the elevated CO_2 case resulted in increased economic well-being for the agricultural sector, but the coarse resolution scenario exhibited larger benefits compared to the fine scale scenario (Table 3), for which the increase was negligible. The change in economic welfare depends primarily on changes in benefits to consumers and producers. Generally, producers lose due to production increases and accompanying price declines while consumers and foreign interests gain. Producer and foreign welfare is not very sensitive to the scenario scale. The main determinant of total economic welfare sensitivity is the level of consumer welfare, which is affected primarily by changes in total production and associated price changes (Table 3). In the elevated CO_2 case, the main determinant of the difference in total welfare was the much larger consumer benefit for the coarse scale scenario (Table 3).

For the adaptation case, total economic welfare values increased further for both scenarios, but more so for the coarse scenario as opposed to the fine scale (Table 3). Hence, even with adaptation, the contrasting economic effect of the scenarios is seen, but relatively speaking, the contrast narrows. The high resolution elevated CO_2 case results in a value for economic welfare 70% less than that of the coarse resolution, while with adaptation the RegCM value is 37% less than the CSIRO value. This decrease in differences is expected since adaptation measures reduce the potential differences in the effect of climate by attempting to mitigate against such changes.

The main cause of contrasting results can be traced back to the contrasts in the changes in yields. In many of the most productive agricultural areas, yields (and by extension, production) is greater for the CSIRO scenario (Table 2).

Regional index numbers for the total value of production, which is a measure of economic activity within the regions, show interesting differences across the regions, based on the scenarios (Table 4). The Southeast shows the largest decreases in activity for both climate scenarios in the elevated CO_2 case, but the decrease with the fine scale scenario is much larger. Appalachia and the Delta States also show decreases for both scenarios with larger decreases for the fine scale scenario. In the Corn Belt region the scenarios result in opposite directions of change in activity for both the

Table 4. Regional economic index numbers. The scenario/cases are: CSIRO: CSIRO (coarse) climate change + elevated CO_2; RegCM: RegCM (fine) climate change + elevated CO_2; CSIROA: CSIRO (coarse) + adaptation; RegCMA: RegCM (fine) + adaptation. Regions listed are the megaregions used in the ASM. The base case has a value of 100.

Scenario/case	North East	Lake States	Corn Belt	North Plains	Appalachia	South East	Delta States	South Plains	Mountains	Pacific
CSIRO	118	145	107	110	82	78	84	135	138	121
RegCM	99	137	79	122	72	67	80	147	129	127
CSIROA	122	158	116	123	85	83	86	147	144	134
RegCMA	106	146	83	141	79	80	86	163	138	138

elevated CO_2 and adaptation cases. The variability of the index numbers across the regions is greater for the fine scale scenario for both the elevated CO_2 and adaptation cases compared to the coarse scale, which likely reflects the greater spatial variability in the fine scale climate changes. The values across all regions for both cases generally indicate greater economic losses in the fine scale climate scenario. Exceptions include the North and South Plains and the Pacific Coast. In this regard, the fact that the results for the fine scale scenario remain closer to zero for the net national effect (total surplus) discussed earlier may reflect the fact that there is something of a canceling out effect occurring across the regions, since the fine scale scenario results in greater highs and lows in the economic welfare. However, this possibility can only be evaluated after many more experiments with other downscaled scenarios are performed.

With adaptation, while the index increases for all regions for both scenarios, those that were below 100 in the elevated CO_2 case remain below 100 in the adaptation case. For these regions, obviously, adaptation cannot completely mitigate the adverse effects of the climate changes. It would be expected that, under conditions of either scenario, but particularly the fine scale scenario, that agricultural activities would diminish for the regions of the Southeast, Delta States, and Appalachia. Hence, the larger area of the Southeast encompassing all these subregions would likely become less competitive in agricultural production, except, perhaps for cotton.

5. CONCLUSIONS

Our analysis demonstrates that the spatial scale of a climate change scenario can substantially affect simulated changes in crop yields and their economic consequences.

These results may be considered limited by the limited number of years of climate model results used to form the scenarios, and the fact that three RegCM runs were used to form the fine scale scenarios. Moreover the differential density of base stations used for calculating baseline and climate change yields adds another (small) uncertainty to our results. However, these limitations are not essentially problematic to our study, which is focused on sensitivity of outcomes (both crop and economic) to assumptions concerning spatial resolution. What is most important is the consistency of the treatment of research elements across the two scenarios so that we can clearly discern the contrasting effects of the climate scenarios alone.

Some uncertainties in climate change impacts research have received more attention than others. For example, different climate models produce different patterns of climate changes for the same forcing, and the effects of these differences have been investigated in numerous studies such as the U.S. National Assessment. In the agricultural component of this assessment [41–43], two very different climate scenarios based on two different global climate models were used. The yield and national economic differences for these two scenarios are similar in magnitude to those due to spatial scale of scenarios we report here. Thus, the uncertainty due to the spatial scale of scenarios can be as large as the uncertainty due to differing global climate model responses.

While we cannot conclude decisively that a regionalized climate scenario is inherently more ‘accurate’, we note that regional models may create more realistic local responses to climate forcing than do coarse scale climate models [11]. The varied physiography of the United States makes it an appropriate land area for exploring the issue of regionalization of scenarios. The potential value of downscaling to obtain more regional precision in climate change impacts studies is important and deserving of further investigation as assessment work goes forward. The difficulty and cost of producing high resolution scenarios may be justified, given the nontrivial effect such scenarios can have on assessment outcomes. However, it is important to view the uncertainty due to spatial scale of scenarios in the context of the other major uncertainties regarding climate scenarios, namely climate model sensitivity and uncertainties regarding future trajectories of greenhouse gases. Scenario development programs considering all three factors should be encouraged, such as the PRUDENCE program in Europe [46]. We encourage the development of a program for North America.

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