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An Assessment of Irrigation Needs and Crop Yield for the United States under Potential Climate Changes

by

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ABSTRACT

Past assessments of climate change on U.S. agriculture have mostly focused on changes in crop yield. Few studies have included the entire conterminous U.S., and few studies have assessed changing irrigation requirements. None have included the effects of changing soil moisture characteristics as determined by changing climatic forcing. This study assesses changes in irrigation requirements and crop yields for five crops in the areas of the U.S. where they have traditionally been grown. Physiologically-based crop models are used to incorporate inputs of climate, soils, agricultural management, and drought stress tolerance. Soil moisture values from a macroscale hydrologic model run under a future climate scenario are used to initialize soil moisture content at the beginning of each growing season. Historical crop yield data is used to calibrate model parameters and determine locally acceptable drought stress as a management parameter. Changes in irrigation demand and crop yield are assessed for both means and extremes by comparing results for atmospheric forcing close to the present climate with those for a future climate scenario. Assessments using the Canadian Center for Climate Modeling and Analysis General Circulation Model (CGCM1) indicate greater irrigation demands in the southern U.S. and decreased irrigation demands in the northern and western U.S. Crop yields typically increase except for winter wheat in the southern U.S. and corn. Variability in both irrigation demands and crop yields increases in most cases. Assessment results for the CGCM1 climate scenario are compared to those for the Hadley Centre for Climate Prediction and Research GCM (HadCM2) scenario for southwestern Georgia. The comparison shows significant differences in irrigation and yield trends, both in magnitude and direction. The differences reflect the high forecast uncertainty of current GCMs. Nonetheless, both GCMs indicate higher variability in future climatic forcing and, consequently, in the response of agricultural systems.

1. Past Assessments of Climate Change on U.S. Agriculture

The effects of climate change on agriculture have been the focus of several investigations over the past decade. Most of these efforts have concentrated on estimating changes in productivity. *Rosenzweig and Parry (1994)* analyzed grain crop yield changes under three separate climate change scenarios (i.e., scenarios generated by general circulation models [GCM's]) at 112 global sites using physiologically-based models. Simulations were conducted both including and omitting increased atmospheric CO_2 concentration effects on plants. Some sites also included irrigated treatments according to soil moisture depletion criteria; however, irrigation quantities, changes in irrigation, and soil moisture values were not reported. Simulation results were input into a set of agricultural sector models to determine economic consequences of agronomic changes. *Easterling et al. (1993)* examined agricultural impacts for a four state region in the central U.S. for an "analog" climate (that of the 1930's) rather than a GCM-forecast climate. Their study also examined the efficacy of farm-level adaptation strategies in counteracting adverse climatic effects. Study results focused on crop yield changes. Other examples of research efforts focusing on crop production include *Brown and Rosenberg (1999)* and *Singh et al. (1998)*.

Assessment studies concentrating on the effects of climate change on irrigation demands have been fewer in number. *Peterson and Keller (1990)* calculated irrigation requirement changes for 39 U.S. counties using a reference evapotranspiration technique. Climate scenarios were formulated in terms of fixed deviations of temperature and precipitation from current values instead of using GCM-forecast climate. Results from the 39 sites were expanded to create irrigation isogram maps for the contiguous U.S. *McCabe and Wolock (1992)* conducted a sensitivity analysis to assess the irrigation requirement response to changes in precipitation, temperature, and stomatal resistance at a single site. *Karim et al. (1999)* included irrigation applications determined by physiological moisture stress in their assessment of crop yield changes in Bangladesh, but they reported yields without irrigation quantities. *Kaiser (1999)* has cited the need for further research into determining the effects of climate change on irrigation demands and the role of irrigation in mitigating adverse climatic effects. The above studies did not explicitly include the role of regional soil moisture, and those that included irrigation demands did not explicitly calibrate the crop models to historical management practices (with the exception of *McCabe and Wolock [1992]*).

2. Scope of This Study

This article addresses potential changes in irrigation needs and crop yield in the U.S. agricultural sector. An analysis using current techniques is performed to investigate how potential scenarios of climate change will affect agricultural water demands under present management criteria and how agricultural production will change under these same scenarios. The assessment is conducted for five economically important crops across their major regions of present cultivation. Conclusions are made for trends in mean values of irrigation demand and crop yield and for trends in the variability of these quantities for local cultivation sites.

This assessment differs from other studies in several important ways. First, the role of climatological effects on regional soil moisture as affecting irrigation demands has not previously been considered. *K. Georgakakos and Smith (2000, companion article)* have demonstrated that regional soil moisture trends and variabilities are strongly affected by changes in climatic forcing. In order to assess changing irrigation requirements with accuracy, future trends in soil water content at the beginning of growing seasons must be included. Second, determination of irrigation requirement has not typically been calibrated to historical practices. Many studies have assessed rainfed agriculture exclusively or have assessed irrigation demands with reference evapotranspiration methods or other “optimum irrigation” quantities. Reference evapotranspiration methods ignore soil moisture availability and tend to overestimate irrigation requirements. Quantification of optimum irrigation neglects the very common occurrence of deficit irrigation (and its reduced crop yields) in agricultural practice. Third, few previous studies have encompassed a spatial extent and resolution adequate to assess local trends throughout the conterminous U.S. for locally important crops. Fourth, most previous studies assessing change in irrigation demands have used sensitivity analysis of irrigation to meteorological parameters rather than consistent climate scenarios. Climatically consistent assessment using GCM scenarios allows for the analysis of trends in means and variability, both of which are important for policy formulation.

The value of this analysis is multifold. First, the number of local cultivation sites extending over a large spatial domain will allow for the identification of local, regional, and national trends. Future policies will likely be influenced by interests at all these scales. Second, by forcing the crop growth models with hydrologically modeled soil moisture scenarios, the irrigation demands derived from the assessment are hydrologically consistent. Third, by assessing physiologically-derived crop yield changes simultaneously with irrigation demand changes, some measure of the marginal value of revised water resources allocations to agricultural users can be made. Fourth, the analysis of trends for several different crops using credible models of crop physiology can allow identification of varying responses to climate change that may influence future agricultural sector planning. Fifth, the identification of physiologically-based moisture stress as an agricultural water resources management criterion represents a consistent framework with which to assess irrigation needs for many other circumstances.

3. Methodology

3.1 Physiologically-based Crop Modeling

Crop growth simulations are herein conducted using the Decision Support System for Agrotechnology Transfer (DSSAT) suite of crop models *(Tsuji et al., 1994).* The DSSAT crop models are a group of physiologically-based models developed and refined by agronomic scientists over the past fifteen years. The models simulate on a daily time step all of the important processes in crop growth and development: daily meteorological forcing, soil temperature, soil water transport, plant water uptake, nutrient transport and uptake, phenological development, photosynthetic production, carbohydrate partitioning, agricultural management inputs, etc. The models account for genotype differences by including cultivar-specific parameters in the input set. For certain crops, damage due to disease and pests can also be included in the simulation. Currently, DSSAT models exist for sixteen crops.

Both the DSSAT models' input and output data sets reflect the richness of the models' simulation capacities. Input parameters include sets of meteorological, crop and management, and soils information. Daily values of precipitation, maximum temperature, minimum temperature, relative humidity, sunshine hours, and wind run comprise the meteorological data. Crop and management values include cultivar, planting date, planting density, row spacing, fertilizer applications, irrigation applications, etc. Soils data for the root zone are used for a multiple horizon profile and include parameters of textural composition, lower limit, drained upper limit, saturation limit, root abundance, bulk density, moisture transport rate, runoff coefficient, etc. Model output includes harvest values of grain or fruit yield, total irrigation applications, and time-series of soil-plant moisture and biophysical parameters. Moisture parameters can include soil moisture content by horizon, plant transpiration, soil evaporation, root water uptake, runoff, and drainage. Biophysical parameters include leaf area index, biomass divided into roots, stems, leaves, and grain, dates of phenological transition, etc.

All DSSAT models share a common water balance sub-model. This sub-model, originally presented by *Jones and Kiniry (1986)*, includes calculation of runoff, downward soil moisture transport, evaporation from soil, transpiration from the plant, root water uptake, capillary rise, and soil moisture content updating. The accuracy of the DSSAT soil water dynamics has been verified by *Ritchie (1972)*, *Jones et al. (1980)*, and *Gabrielle et al. (1995)*, and will be additionally verified later in this paper. A soil water deficit factor is computed as a ratio between root water uptake and transpirative demand. Periods of moisture stress are thus identified when transpirative demand exceeds root water uptake indicating that the plant has a net loss of water that day. This moisture stress parameter will form the basis of the irrigation scheduling methodology to be discussed later.

Plant physiological response to increased atmospheric CO_2 is also included in the DSSAT models, this component being especially suitable for this assessment. Comparison of simulation results for constant CO_2 and increasing CO_2 cases showed that all crops produced higher yields under increasing CO_2 concentration (Figure 1a). Irrigation demands were only negligibly changed except for corn where irrigation demand decreased under the increasing CO_2 scenario (Figure 1b).

All simulations allowed crop growth to occur without constraints due to limited nutrients (e.g., nitrogen), pests, or diseases. (The DSSAT models do include routines to assess the effects of these factors on plant growth and development). Because most agricultural production in the United States utilizes effective programs of fertilization, pest control, and disease control, the omission of these factors in simulation does not significantly force model outputs to deviate from observed patterns. The effect of these omissions is to focus the assessment on the effects of climate forcings on irrigation demands and crop yield with other factors being held constant.

3.2 Assessment Input Data

As stated, the DSSAT crop models require extensive input data of meteorology, crop and management, and soil parameters. Crop genotype parameters are included in the DSSAT software database, and management parameters other than irrigation were set to standard values. The assessment was carried out using climate divisions as the basic spatial unit of analysis. This spatial scale coincides with the resolution of the hydrologic model that was used to provide climatically consistent regional soil moisture sequences *(K. Georgakakos and Smith, 2000, companion article)*. Thus, all spatially varying data were taken from the data sources as one data set for each climate division. Typically, data corresponding to the site closest to the centroid of the division were used, although some exceptions were made and are described in turn and many input data were regionalized values. Due to this regionalization of much of the input data, the correct interpretation of this assessment for each location is that the irrigation demand and crop yield are representative of a site which experiences regionally averaged conditions.

Soil data were derived from the U.S. Department of Agriculture Natural Resources Conservation Service State Soil Geographic Database (STATSGO) *(NRCS, 1994)*. The soil type lying at the climate division centroid was chosen to be representative of the entire division unless another soil type was seen to cover a predominant portion of the division area. In most cases, both criteria yielded the same choice of soil.

Characteristics of the changed future climate were taken from the outputs of the Canadian Centre for Climate Modeling and Analysis Global Coupled Model 1 (CGCM1) *(CCCMA, 1997)*. The CGCM1 is a coupled atmosphere-ocean model having a surface resolution of approximately 3.7º x 3.7º and ten vertical levels. It includes an increase in atmospheric CO_2 at a 1% annual growth rate and the effect of sulphate aerosols. The CGCM1 outputs have been projected onto a 0.5º x 0.5º grid as part of the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) *(Kittel et al., 1997)*. This finer resolution grid allows for greater spatial specificity in determining local climate characteristics. Spatial downscaling of values from the 3.7° x 3.7° CGCM1 grid to the .5° x.5° VEMAP grid was conducted by spatial interpolation of differences between model future and model control values added to historical baseline values *(Taylor and Felzer, 1999)*. Temporal resolution of outputs in both the original CGCM1 and VEMAP datasets is monthly. Downscaling of monthly values to daily values is discussed in the next section. The CGCM1 is used at the recommendation of the U.S. National Climate Change and Variability Assessment to ensure consistency across various assessment sectors and activities. However it should be viewed as one of several possible choices. For comparison, some assessment results were also obtained using the U.K. Meteorological Office Hadley Climate Model version 2 (HadCM2) *(UKMO, 2000)*. The results from the two models are different indicating the range of uncertainty characterizing GCM predictions.

The differences between the observed historical climate and the historical climate modeled by the CGCM1 have been noted in the companion article *(K. Georgakakos and Smith, 2000)*. The localized differences between observed and modeled values vary, but they are appreciable in some places. Thus, assessment results forced by historical climate compared against results forced by modeled climate (historical or future) would yield an inconsistent review. For this reason, this assessment utilized two periods of the CGCM1 modeled future climate as forcing for the comparison sets. The first period is the modeled climate for years 1994 to 2013. This period was chosen as being representative of the current climate as it would not entail large CO_2 increases and climate forcing changes. The second period is the modeled climate for years 2041 to 2060. This period represents the future climate after significant CO_2 accumulation and climatic changes.

The assessment includes crop growth simulations for five different crops: corn, durum wheat, peanuts, soybeans, and winter wheat. For each crop, simulations are conducted in localities where the crop has historically been grown in abundance and contributed appreciably to the national production. To establish the spatial distribution of cultivation for each crop, maps of harvested acreage by county were obtained from the National Agricultural Statistics Service *(NASS, 1999b)*. These maps are reproduced in Figures 2a-2e. Considering the 1998 U.S. production of these five crops and their commodity market prices at the time of harvest for that year, the “farmgate” economic value of these crops is more than $44 billion *(NASS 1999a, CBOT 2000)*.

3.3 Assessment Process

3.3.1 Downscaling of Monthly Climatology

Daily meteorology was derived from the monthly meteorological outputs of the CGCM1 as projected onto the VEMAP grid. The monthly values were downscaled to daily values by use of the WGEN stochastic weather generator *(Richardson, 1981).* Seven weather stations having continuous data in the six needed parameters (precipitation, maximum temperature, minimum temperature, relative humidity, sunshine hours, and wind run) were chosen as base stations. The records from these base stations were analyzed to calculate base parameters for Markov transition probabilities of precipitation and autocorrelation/cross-correlation values for all other parameters. Sequences of daily meteorology for the modeled future climate were generated for each climate division using the base parameters of an appropriate base station (Figure 3) and the monthly values of the VEMAP grid cell nearest the centroid of the climate division. Thus, the assumption has been made that the statistical properties of transition probabilities, autocorrelation, and cross-correlation in meteorological parameters is preserved at historical values. In all cases, the monthly means or sums (as appropriate) of the generated daily values were equal to the CGCM1 monthly values.

3.3.2 Soil Moisture Forcing

In physiologically-based crop modeling, the inclusion of explicit soil-plant moisture water balance makes initialization of soil moisture content very important. It is not uncommon for a specific site’s soil to have a plant-extractable soil water capacity (i.e., water content between the lower limit and the drained upper limit) in the root zone equal to mean growing season precipitation for six weeks or more. Thus, an incorrect soil water initialization that overestimates soil water content at the beginning of the growing season could seriously inflate crop yield predictions. Likewise, an underestimation of initial soil water content could discount the importance of pre-season rains and yield inflated irrigation demands. The DSSAT soil moisture sub-model can be used for fallow ground to simulate inter-seasonal periods. However, the sub-model does not include routines for dealing with phenomena such as frozen ground and snowcover. Thus, pre-season soil moisture conditions in locations experiencing these events are not reliable.

To ensure that soil moisture conditions at the beginning of the growing season are regionally and climatically consistent, their values were computed using a macroscale hydrologic model over the contiguous United States *(K. Georgakakos and Smith, 2000, companion article)*. This model has a monthly time step and uses climate divisions as basic spatial units. The model has been run with a variety of forcings including observed historical data, a CGCM1 control run (i.e., the CGCM1 simulation of the present climate), and a CGCM1 changing climate run that includes increasing atmospheric CO_2. The soil moisture conditions thus generated were used to initialize the DSSAT water balance submodel at the beginning of each growing season, ensuring that the climatological and soils input data sets were consistent between the macroscale hydrologic model and the crop simulations. Lastly, as discussed later in this article, the ability of the DSSAT water balance submodel to simulate soil moisture changes *within* each growing season is deemed to be adequate.

3.3.3 Drought Stress as a Management Criterion

One of the principal goals of this assessment is to diagnose future trends in irrigation demands for a variety of crops and locations. Assessment of irrigation needs under a changing climate is not a straightforward issue, however. Traditional irrigation scheduling techniques based upon reference evapotranspiration can be shown to often overestimate irrigation needs due to their omission of soil moisture storage capacity. Furthermore, these methods rely on empirical crop-specific evapotranspiration coefficients derived from past experience; due to changing physiological responses to increased atmospheric CO_2, the validity of these coefficients is not guaranteed.

Another complication pertains to calibrating crop yield models to historical conditions. This task is made quite difficult for two reasons. First, throughout large portions of the United

States, especially east of the Rocky Mountains, crop acreage is an unquantified mixture of irrigated and rainfed production. Data on the extent of production relying on irrigation, even where they exist, can be unreliable since some irrigation systems are very portable and may be used under a variety of configurations over several seasons. Second, data on actual irrigation applications as water volume or depth are equally difficult to find. In fact, in many states data on irrigated acreage are more readily available since they can be gathered quickly without intensive, long-term monitoring. Western states often have public records of water withdrawal rights owned by agricultural users, but these rights are not always fully utilized, nor is there assurance that water application is conducted at full efficiency.

Physiologically-based crop models offer a means by which irrigation needs can be determined that are both responsive to climatic and physiological forcing and can be grounded in current irrigation practices. As mentioned above, the water balance sub-model common to the DSSAT crop models includes computation of a soil water deficit or moisture stress parameter. This parameter can be used as an irrigation scheduling tool by setting a user-defined threshold that triggers irrigation application. In this assessment, ten-day composite moisture stress values were computed in each growing season. For periods having drought stress beyond the allowable moisture stress threshold (MST), appropriate irrigation applications were determined to bring the stress value just inside the allowable range. MST values are an implicit agricultural management criterion that reflects the farmer's propensity to apply irrigation. In some locations, irrigation may be used often which is reflected in a low MST value. Other sites may have higher drought tolerance and may require less irrigation resulting in higher MST values.

The MST values were herein used as a calibration parameter to bring long-term trends in simulated crop yields under historical conditions in line with observed values. These MST thresholds were then used to assess the agricultural response of future climate scenarios. Thus, the basic supposition is that the farmers' irrigation attitude as gauged by the MST will remain unchanged. The calibration procedure and results are described below.

It should be noted that the physiological and soil moisture components of the DSSAT crop models allow for identification of influences on irrigation demand beyond the range of traditional approaches. The soil moisture initialization procedure described above allows for incorporation of changes in soil water characteristics due to climatic changes outside of the growing season. Likewise, plant physiological characterizations can reveal responses to changed climate and atmospheric content unavailable to traditional methods (e.g., increased CO_2 leading to stomatal closure and reduced transpirative potential).

3.3.4 Assessment Criteria

Future trends in irrigation needs and crop yield were assessed for U.S. climate divisions for five crops: corn, durum wheat, peanuts, soybeans, and winter wheat. Trends were identified by comparing modeled irrigation requirements and crop yields for two climatic periods as modeled by the CGCM1. Years 1994 to 2013 were used as a surrogate for the current climate with minimal accumulated climate change effects, and years 2041 to 2060 were used to represent the significantly changed future climate. All crop growth simulations included atmospheric CO_2 increasing over time at 1% compounded annual growth rate.

The assessment included evaluation of trends in both irrigation and yield mean values as well as values corresponding to extreme events (i.e., severe drought, extreme cold, and other adverse meteorological extremes). The twenty growing seasons in each assessment period allowed for derivation of an empirical frequency distribution of irrigation needs and crop yield for each crop. From this distribution, percentile values could also be determined. The ninetieth percentile of irrigation requirements was chosen as the level representing drought extremes. Unfavorable yield extremes were represented by the tenth percentile of crop yields. By examining the difference in the mean and the extreme values, the change in the "spread" of the frequency distribution was identified and quantified the change in variability in irrigation and yield.

4. Calibration

4.1 Soil Moisture

As stated above, the soil moisture sub-model of the DSSAT crop models represents an essential simulation component by including soil water storage capacity as a moisture source for the plant. The importance of soil moisture processes is underscored by the initialization procedures employed. The following test was conducted to verify that DSSAT accurately reproduces soil moisture conditions within each growing season. The test was based on measured soil moisture values for Peoria, Illinois, obtained from the Illinois State Water Survey for the period 1987 to 1992 *(Hollinger and Isard, 1994)*. Simulations were conducted for growing seasons only, as frozen ground and precipitation during winter months would not be accurately modeled by DSSAT. Model soil moisture profiles were set equal to observed values at the beginning of each growing season.

Comparison of observed and modeled soil water content is shown in Figure 4. With the exception of the second half of the 1990 growing season, there is good agreement between the two sets of values both in terms of soil moisture magnitude and timing of magnitude changes. This agreement is consistent throughout the range of soil water content observed during growing seasons. In seeking to explain the inconsistency seen in the second half of the 1990 growing season, the precipitation record for the Peoria station was compared to three nearby stations. The Peoria gauge had uncharacteristically high recorded rainfall for July 1990. Thus, it appears that the Peoria raingauge measurement was not representative of the regional rainfall in the summer of 1990. In summary, this test indicates that the DSSAT soil moisture representation is a valid one provided that it is correctly initialized.

4.2 Crop Yield and Moisture Stress Threshold

As discussed above, the physiologically derived drought stress index computed in the DSSAT models provides a means by which to efficiently schedule irrigation. Furthermore, a user-defined moisture stress threshold (MST) may be employed as an agricultural water resources management parameter. Determining appropriate MST values was the subject of a calibration procedure that aimed to match modeled crop yields to historically observed yields.

Observed historical local crop yields were gathered from the National Agricultural Statistics Service *(NASS, 1999a)*. These observed yields were available for all five crops of interest in this assessment. Using observed historical time-series of monthly meteorology (as assimilated by the VEMAP project) and initial soil moisture values from historical climate runs of the *K. Georgakakos and Smith (2000)* model, crop yields and irrigation demands were determined for each crop, state-by-state. The historical monthly values of meteorology were downscaled to daily values using the procedure described above to ensure consistency with the downscaled CGCM1 values. However, because of this process, the actual daily time-series of meteorology were not used. Thus, crop responses to inter-daily phenomena could not be exactly replicated, and it was not expected to have high correlation of individual pairs of measured and simulated values. (The differing scales of regional aggregation in the measured and simulated values contribute another source of disagreement.) Instead, the aim of the calibration process was to match the mean, variance, and general temporal trends in yield of simulated values to those of measured values. Figures 5a-5e show example calibration results for each of the five crops included in the assessment. Irrigation demands computed in the calibration runs were in-line with expectations. Namely, arid regions tended to have considerable irrigation needs in all years with crop yield being highly sensitive to variations in MST, and humid regions only required irrigation sporadically during occasional dry years. MST values were held constant for all future climate scenario simulations at their calibrated values, implying that decision-makers' drought tolerance will be in the future similar to what it is now even as climate changes occur.

5. Assessment Results

The results of the assessment are presented in both tabular and graphical form and are discussed below. The tables present results aggregated into the regions mapped in Figure 6. Regional mean changes in irrigation needs are shown in Table 1a, and regional mean changes in crop yields are given in Table 1b. In both of these tables, the percentage change with respect to the irrigation or yield value in the initial period is given in parentheses. Changes in variability of irrigation requirements and crop yields were also computed and are presented in Table 1c (irrigation requirements) and Table 1d (crop yield). A change-in-variability statistic was computed as the ratio of the difference of the extreme and mean in the future climate to the difference of the extreme and mean in the present climate. Values of this statistic greater than one indicate increased variability, and values less than one indicate decreased variability. The typographical convention for these ratios is to show values representing variability increases as underlined and values representing variability decreases in italics. Maps presenting assessment results are shown in Figures 7-11.

5.1 Peanuts

Peanut cultivation was simulated for the Southeastern Coastal Plain and the Southern Great Plains. The growing season for peanuts typically starts in mid-May and ends in late summer. All cultivation regions for peanuts had increased irrigation demands for future climate over those of the current climate both for means and ninetieth percentile values (Figure 7). Southeastern Coastal Plain divisions had increases in mean values as high as 52 mm (2.04 in) and extreme values increases as much as 100 mm (3.94 in). Southern Great Plains divisions had increases in mean irrigation needs by as much as 45 mm (1.78 in) and ninetieth percentile increases as much as 35 mm (1.38 in). One division in Texas did have changes considered insignificant for both means and extremes. For the Southeastern Coastal Plain, the fact that extreme irrigation demands had a higher increase than the means indicates that the CGCM1 predicts that future droughts will increase both in number as well as in intensity. As a consequence, the variability of the future irrigation needs will also increase. In general terms, the Southeastern Coastal Plain's mean irrigation needs for peanuts increase by about 100%, and the Southern Great Plains mean irrigation needs for peanuts increase by about 50%.

Assuming that the previous irrigation demands are met, peanut yield changes were more spatially heterogeneous. Southeastern Coastal Plain areas had significant increases in mean yields typically on the order of 900 kg/ha (813 lb/acre). Tenth percentile yields for the Southeast were largely changed only by negligible amounts. As was the case for irrigation demands, these two trends indicate increased variability in peanut yields for the Southeastern Coastal Plain. This implies that while CO_2 increases are expected to enhance average crop yield under similar soil moisture conditions (created by additional irrigation), during extreme droughts the CO_2 enhancement becomes limited by climatic factors other than soil moisture availability. Southern Great Plains divisions had negligibly changed peanut yields in both means and extremes with the exception of mean yields in New Mexico.

5.2 Durum Wheat

Durum wheat cultivation was simulated for the Northern Great Plains and the California San Joaquin Valley. These two regions have somewhat different growing seasons for durum wheat. Planting in the San Joaquin Valley is typically in mid-December with harvest in late Spring; the Northern Great Plains region plants durum wheat in early May and harvests in late Summer. Irrigation requirements were changed by only negligible amounts for climate divisions in the Northern Great Plains for both mean and extreme values (Figure 8). In contrast, the San Joaquin valley had a large decrease in irrigation need for means and extremes. Specifically, the change in the mean was 96 mm (3.78 in), and the change in the ninetieth percentile value was 98 mm (3.86 in). These quantities represent about 80% of current mean irrigation needs. The CGCM1 modeled future climate predicts increased precipitation in central California, which is in keeping with the modeled change in irrigation demand.

Crop yield changes for durum wheat were positive in both cultivation regions in both means and extremes. Increases in mean yields were typically about 1000 kg/ha (14.9 bu/acre). Increases in tenth percentile yields were more heterogeneous ranging from about 500 to 1300 kg/ha (7.5 to 19.4 bu/acre) with most divisions having lower increases for extremes than for means. Again, these trends indicate increased yield variability for most locations in the future climate, and as in the case of peanuts above, yield response to CO_2 fertilization is inhibited during drought periods.

5.3 Soybeans

Soybean cultivation was simulated for climate divisions in the Eastern Midwest, Southern Great Plains, Upper Mississippi Delta, Northeast, and Southeastern Coastal Plain. The growing season for soybeans lasts from mid-May to late summer. Changes in irrigation requirements exhibited strong spatial trends (Figure 9). Climate divisions in the southern half of the cultivation area tended to have increases in irrigation requirements; divisions in the northern part of the cultivation area tended to have unchanged irrigation requirements. The dividing line between the two areas was located at roughly 40º latitude. Irrigation demand increases in the southern cultivation area were greater for extreme (ninetieth percentile) values than for means. Some increases were quite large in magnitude, such as the ninetieth percentile changes in the Upper Mississippi Delta on the order of 90 mm (3.54 in). The differing magnitude of changes in means and extremes suggested increased variability in irrigation demands for the southern cultivation area. The northern half of the cultivation area was inferred to have unchanged irrigation demand variability. Expressed as percentages, mean irrigation increases were about 100% in the Southern Great Plains, 150% in the Southeastern Coastal Plain, 140% in the Upper Mississippi Delta, and negligibly changed elsewhere.

Changes in mean soybean yield exhibited fewer spatial trends. Mean yields uniformly increased in all areas of cultivation, with typical increases on the order of 800 to 1000 kg/ha (11.9 to 14.9 bu/acre). Changes in tenth percentile yields were more spatially heterogeneous. Most of the southern cultivation range had negligible changes. The largest changes occurred in a narrow belt extending from southwestern Nebraska to southwestern Wisconsin where increases were typically about 1200 kg/ha (17.8 bu/acre). For the remainder of the cultivation area, tenth percentile yields did not increase as much as mean yields. Thus, yield variability is seen to increase for most locations under the future climate.

5.4 Winter Wheat

Winter wheat cultivation was simulated across large areas of the U.S. including the Southeastern Coastal Plain, Northeast, Upper Mississippi Delta, Eastern Midwest, Southern and Northern Great Plains, Snake-Columbia Valley, and California Central Valley. The growing season for winter wheat is quite different from the other four crops in the assessment as it extends from mid-Autumn through mid to late spring. Even so, changes in irrigation requirements exhibited strong spatial trends that agreed with those seen in analyses of other crops (Figure 10). Irrigation needs increased for the Southeastern Coastal Plain and Southern Great Plains climate divisions. These areas had roughly equivalent levels of increase for mean and ninetieth percentile values, except for the southern portions of Alabama and Georgia and northern Texas which exhibited larger increases in the extremes than in the means indicating increased demand variability. The magnitude of increases in these regions was on the order of

20 mm (0.79 in). The Eastern Midwest and Upper Mississippi Delta had negligibly changed or slightly decreased irrigation demands in means and extremes. The Northeast, Northern Great Plains, Snake-Columbia Valley, and California Central Valley all had appreciable decreases in irrigation demands for winter wheat. In these areas, the ninetieth percentile demand values tended to increase more than the means suggesting a decrease in irrigation demand variability under the future climate. Expressed as percentages, mean irrigation increases were about 50% in the Southern Great Plains and 75% in the Southeastern Coastal Plain. Mean irrigation decreases were about 60% in California, 25% in the Snake-Columbia Valley, 45% in the Northern Great Plains, and 75% in the Northeast.

Crop yield changes for winter wheat also followed strong spatial patterns, yet these patterns were somewhat different from the changes in irrigation requirements. In general, climate divisions in the southern portions of the entire cultivation range had negligible yield changes or slight increases. This pattern was found in the Southeastern Coastal Plain, Upper Mississippi Delta, Southern Great Plains, and California Central Valley for both means and tenth percentile yields. The northern regions of cultivation tended to have stronger increasing trends in yield. Moreover, tenth percentile yields changed more than mean yields suggesting decreased yield variability especially in the northwestern divisions. While increased atmospheric CO_2 content would be expected to trigger yield increases in the future climate, the observed strong north-south gradient is related to growing season temperature changes. Winter wheat requires cooler temperatures during specific phenological stages; climatic warming could deny these "vernalization" periods to the plants, especially in the warmer climates of the southern U.S.

5.5 Corn (Maize)

Corn cultivation, like that of winter wheat, was simulated for large regions across the U.S. Corn's growing season is from mid-May to late summer. Compared to the other assessment crops, corn's differing physiological responses to a changed climate and atmospheric CO_2 concentration produced results with peculiar features. Under current management parameters, irrigation demands for corn exhibit a strong west-east gradient with little irrigation demand in the Eastern U.S. and steady demands west of approximately the 102nd West Meridian.

This east-west gradient was also seen in the changes in irrigation needs under the future climate (Figure 11). Eastern climate divisions had negligible change from their small irrigation requirements in means and ninetieth percentile values. Western climate divisions had strong decreases in irrigation demands in both cases. Ninetieth percentile value changes tended to be greater than mean changes indicating decreased variability in demands in the West. The magnitude of changes in means was on the order of 75 mm (2.95 in) in central California and 30 mm (1.18 in) in the Snake-Columbia Valley. Inspection of seasonal water balance for corn simulations shows significantly reduced transpiration as atmospheric CO_2 increases (Figure 12). This phenomenon, along with increased western U.S. precipitation in the CGCM1 future climate, explains much of the decrease seen in irrigation requirements. For the Southeastern Coastal Plain, Northeast, and Eastern Midwest, irrigation demands were virtually eliminated in the few locations where they formerly existed. Irrigation demands decreased in the Southern Great Plains by 50%, in the Snake-Columbia Valley by 40%, and in California by 45%.

Yield changes for corn showed more variation than for any other crop. Mean yields were slightly decreased for most of the U.S. with the exception of the Snake-Columbia Valley. Tenth percentile yield changes were similar. The extreme Northern Great Plains had substantial yield increases. The rest of the cultivation area had negligibly changed or slightly decreased yields. Yield variability was thus increased in the Snake-Columbia Valley, and other areas had minimally changed yield variability.

6. Assessment of Changes Under Alternative Climate Scenarios

The assessment results presented above were obtained by evaluating future irrigation demands and crop yields under the climate predicted by the CGCM1 model. To escape the dependence of assessment results on a single model's peculiarities, the assessment process was conducted again using the climate predictions of the U.K. Meteorological Office Hadley HadCM2 *(UKMO, 2000).* Soil moisture values from *K. Georgakakos and Smith (2000, companion article)* were not available for the Hadley future climate scenario. Soil moisture content was instead derived using a watershed hydrologic model run for both the CGCM1 and Hadley scenarios for the Apalachicola-Chattahoochee-Flint (ACF) watersheds *(A. Georgakakos* *and Yao, 2000).* The ACF basin includes portions of northern and western Georgia, eastern Alabama, and northwestern Florida. Crop simulations were repeated for southwestern Georgia using the same process as above with the substitution of initial soil moisture values from the ACF watershed model. Both the CGCM1 and Hadley climates were simulated using the ACF model soil moisture values to ensure that comparisons would be made on a consistent basis. Assessment results using the ACF model soil moisture values were compared to the results presented above, and the differences found were negligible. Assessments were made for peanuts, winter wheat, and corn.

Comparison of assessment results for the two climate scenarios is presented in Table 2. For peanuts, the Hadley future climate was more favorable than that of the CGCM1. Irrigation demands actually slightly decreased for mean values, and the ninetieth percentile value increased by 12 mm, much less than the 51 mm increase under the CGCM1. Peanut yields increased for both the mean value and the tenth percentile value at a higher level than the CGCM1 results, with the relative change indicating an increase in yield variability for both models. The changes in the frequency distributions of irrigation demands and crop yield are presented for peanuts in Figures 13 and 14. These comparisons show that the changes predicted by the Hadley GCM would require less irrigation and result in greater yields for peanuts in southwestern Georgia than the changes predicted by the CGCM1. It should be noted that where CO_2 fertilization effects on yield were negated during droughts under the CGCM1 scenario, this phenomenon did not occur for the Hadley scenario; instead, crop yields increased throughout the frequency distribution as a result of a more favorable climatic forcing.

Comparison of assessment results for corn showed similar trends in irrigation demand, i.e., a virtual elimination of irrigation needs for the future climate under both scenarios (Table 2 and Figure 15). The comparison of changes in corn yields, however, was especially striking. Whereas yields decreased throughout the frequency distribution for the CGCM1 scenario, yields increased throughout the distribution under the Hadley future climate (Figure 16). Winter wheat results were similar to the other crops. Irrigation requirements decreased under the Hadley scenario whereas they increased under the CGCM1 (Figure 17). Winter wheat yields significantly increased for the Hadley climate where they had changed negligibly for the CGCM1 (Figure 18).

This comparison highlights the uncertainty surrounding future climate forecasts. However, both scenarios indicate an increase in climate variability and, consequently, variability in irrigation demand and crop yield for this site in southwestern Georgia. The differences in agricultural response as forced by the two different climate applies strictly for the southeast. Further assessment to determine the extent of difference or similarity in other regions of the United States under the two climate scenarios is needed.

7. Conclusions

The assessment methodology presented in this paper has introduced a new process, founded on current techniques, to understand the implication of climate change on the agricultural and water resources sectors. Trends in changing irrigation requirements and crop yields across the United States under a scenario of future climate change have been presented for five important field crops. Changes in mean values, drought extremes, and variability were identified. The assessment crops had areas of cultivation that in total extended across most of the contiguous U.S. allowing for diagnosing important spatial trends.

The general conclusions of this assessment effort are as follows. Under the CGCM1 climate scenario, irrigation demands (mean trends and variabilities) and crop yields would increase in the Southeastern Coastal Plain, Upper Mississippi Delta, and Southern Great Plains for most crops. The Eastern Midwest would see negligible or small changes in irrigation demands for most crops. The Northern Great Plains would experience decreased irrigation requirements for winter wheat and unchanged needs for spring and summer-season crops. The Snake-Columbia Valley and California Central Valley would have strongly decreased irrigation demands for all crops. Crop yields would, in general, increase at all locations with the exception of corn yields. The relative magnitude of these changes in yields varies from region to region. These assessment results are in agreement with the CGCM1 climate scenario's trends of a wetter climate in the west, a dryer climate in the east, and warmer temperatures throughout the U.S. Depending on which particular factor is most limiting for crop growth over the growing season (i.e., water availability, temperature, or both), the U.S. agricultural response exhibits marked regional changes in a west-to-east direction around the 104th meridian for corn, a north-to-south direction around the 40th parallel for soybeans and durum wheat, and a northwest-to-southeast direction for winter wheat.

The moisture stress threshold (MST) criterion has been used to incorporate crop management preferences into the assessment by calibration to historical observations. These preferences can then be projected into future scenarios influenced by CO_2 increases.

Identification of future trends in irrigation demand and crop yield must be made using multiple future climate scenarios. Changes in these quantities may be significantly different under various scenarios both in magnitude and in direction. The differences in assessment results under distinct climate scenarios must be understood as a result of uncertainty of the future climate. As climate modeling improves and uncertainty decreases, the assessment methodology presented here may be repeated.

This assessment did not include consideration of the effects of adaptive management measures such as changed planting date, geographic relocation of crops, alternative cultivars, etc. These measures may hold promise in mitigating or enhancing changes in irrigation demand and crop yield due to climate change. Further research is warranted to determine the benefits of adaptive management. To this end, this study may be used as a baseline by which the relative mitigation or enhancement due to adaptation may be determined.

In 1998, the five crops included in this assessment had a combined farm-to-market value of over $44 billion *(NASS 1999a, CBOT 2000)*, a significant portion of U.S. agricultural production. Moreover, in many areas, especially in the Western U.S., agriculture is the predominant consumer of regional water resources. This assessment has contributed in understanding the future trends that may occur as anthropogenic influences may induce climate changes. National policy formulation should consider the conclusions of studies such as this one but also should consider the uncertainty of future climate predictions.

Acknowledgements

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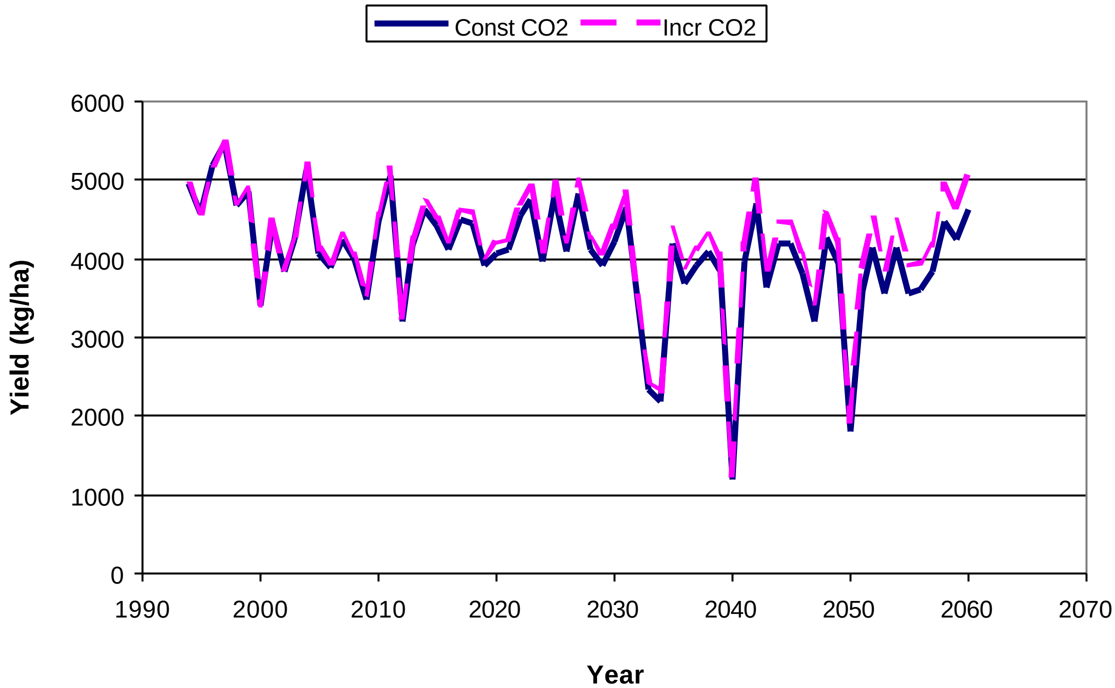


Figure 1a. Effect of Increasing CO2 on Corn Yields in Southwest Georgia

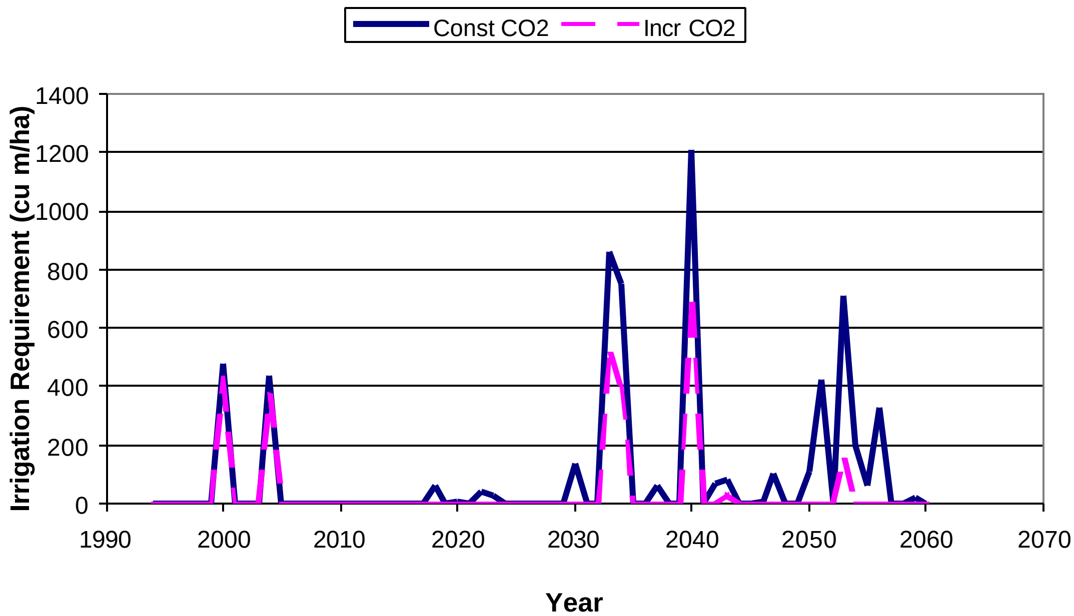


Figure 1b. Effect of Increasing CO2 on Corn Irrigation Demands in Southwest Georgia

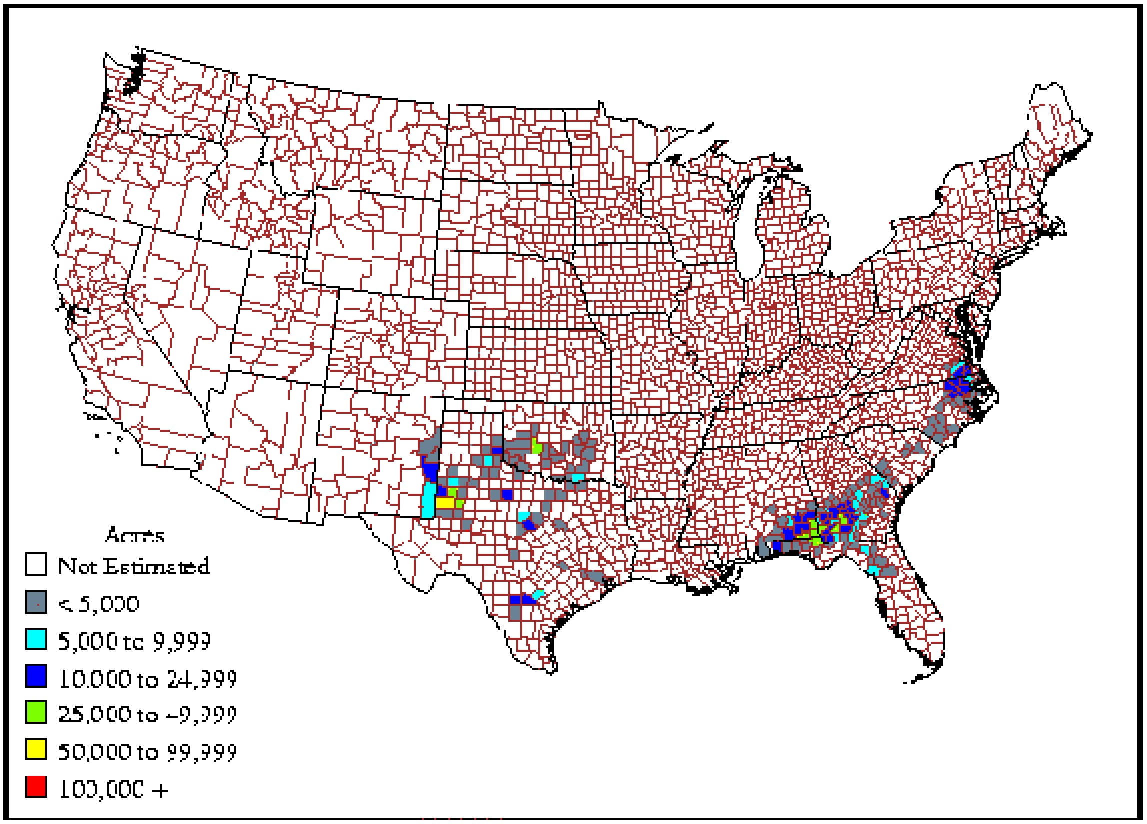


Figure 2a. Harvested peanut acres by county, 1998 *(NASS, 1999b)*

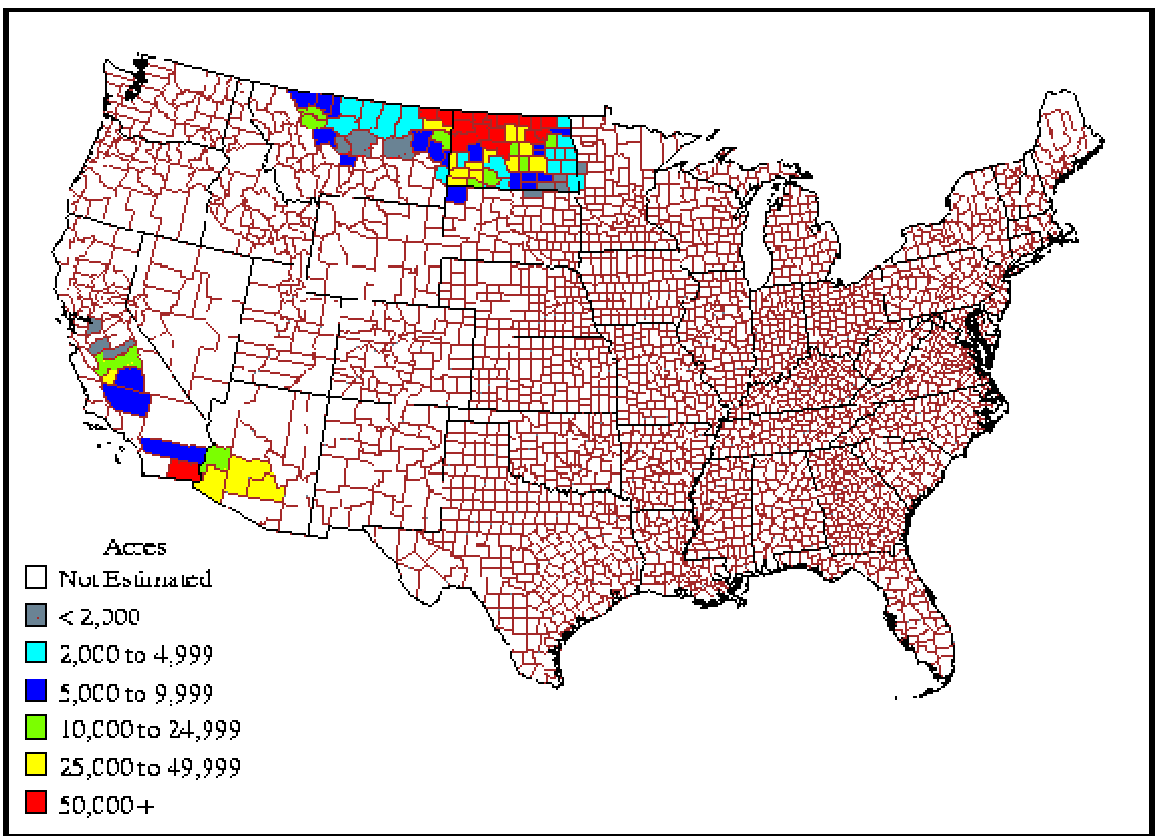


Figure 2b. Harvested durum wheat acres by county, 1998. *(NASS, 1999b)*

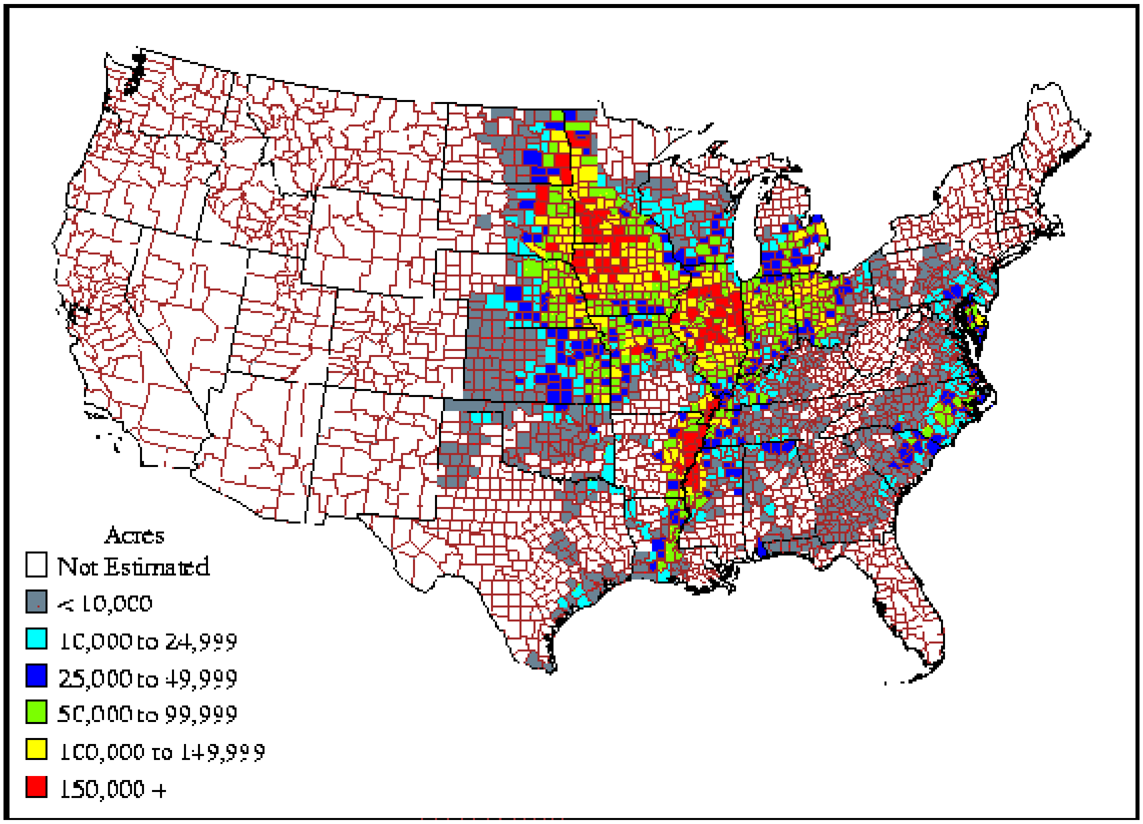


Figure 2c. Harvested soybean acres by county, 1998 *(NASS, 1999b)*

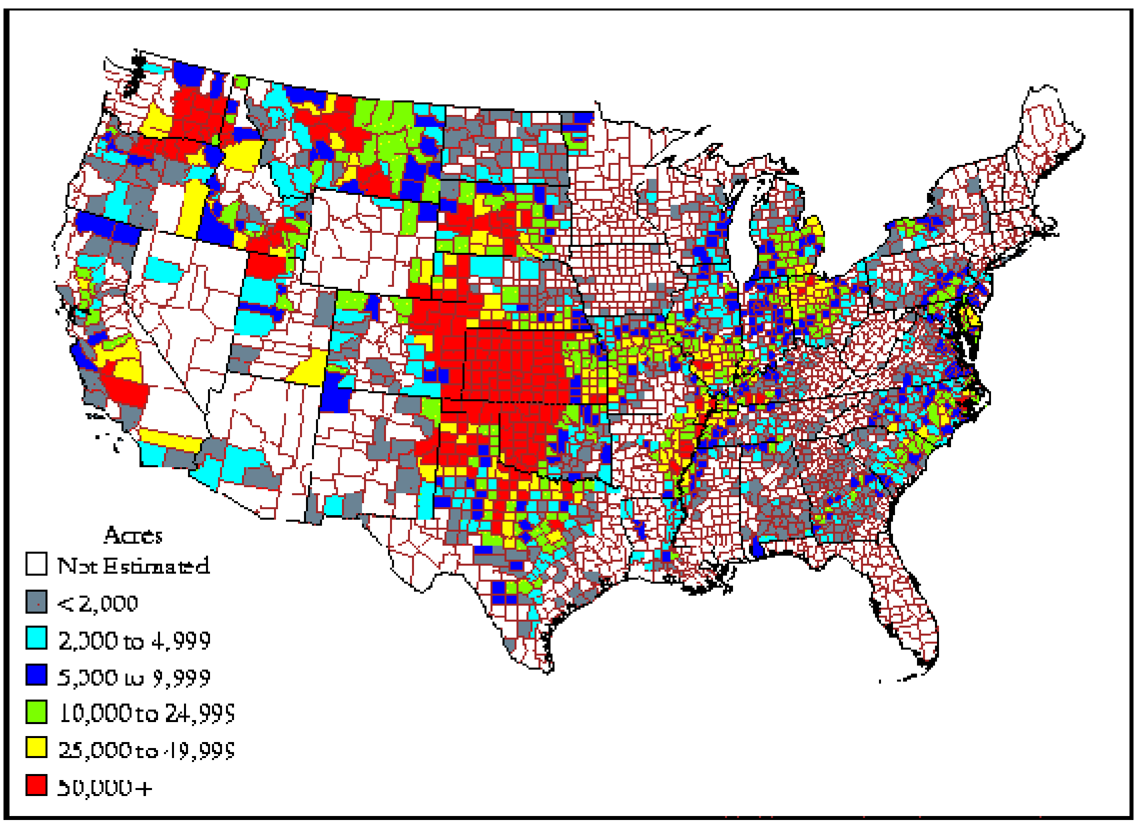


Figure 2d. Harvested winter wheat acres by county, 1998. *(NASS, 1999b)*

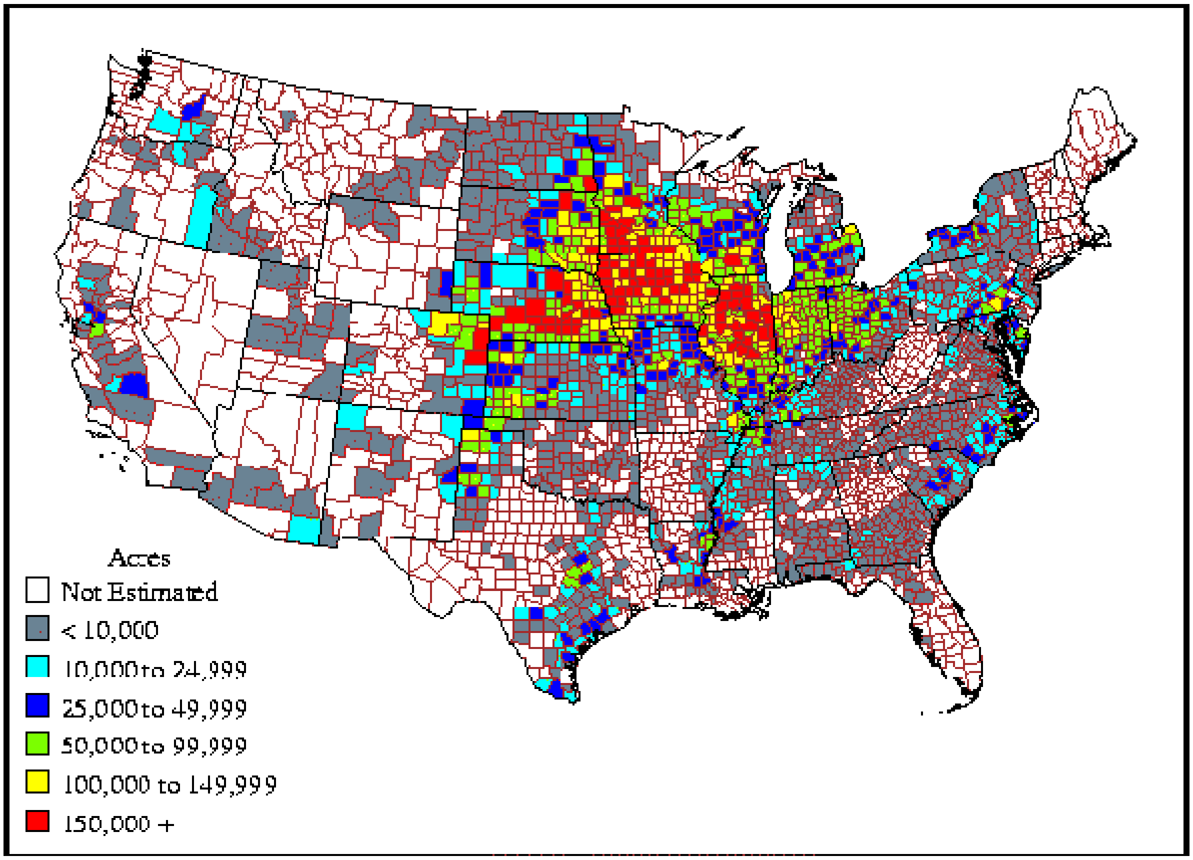


Figure 2e. Harvested corn acres by county, 1998. *(NASS, 1999b)*

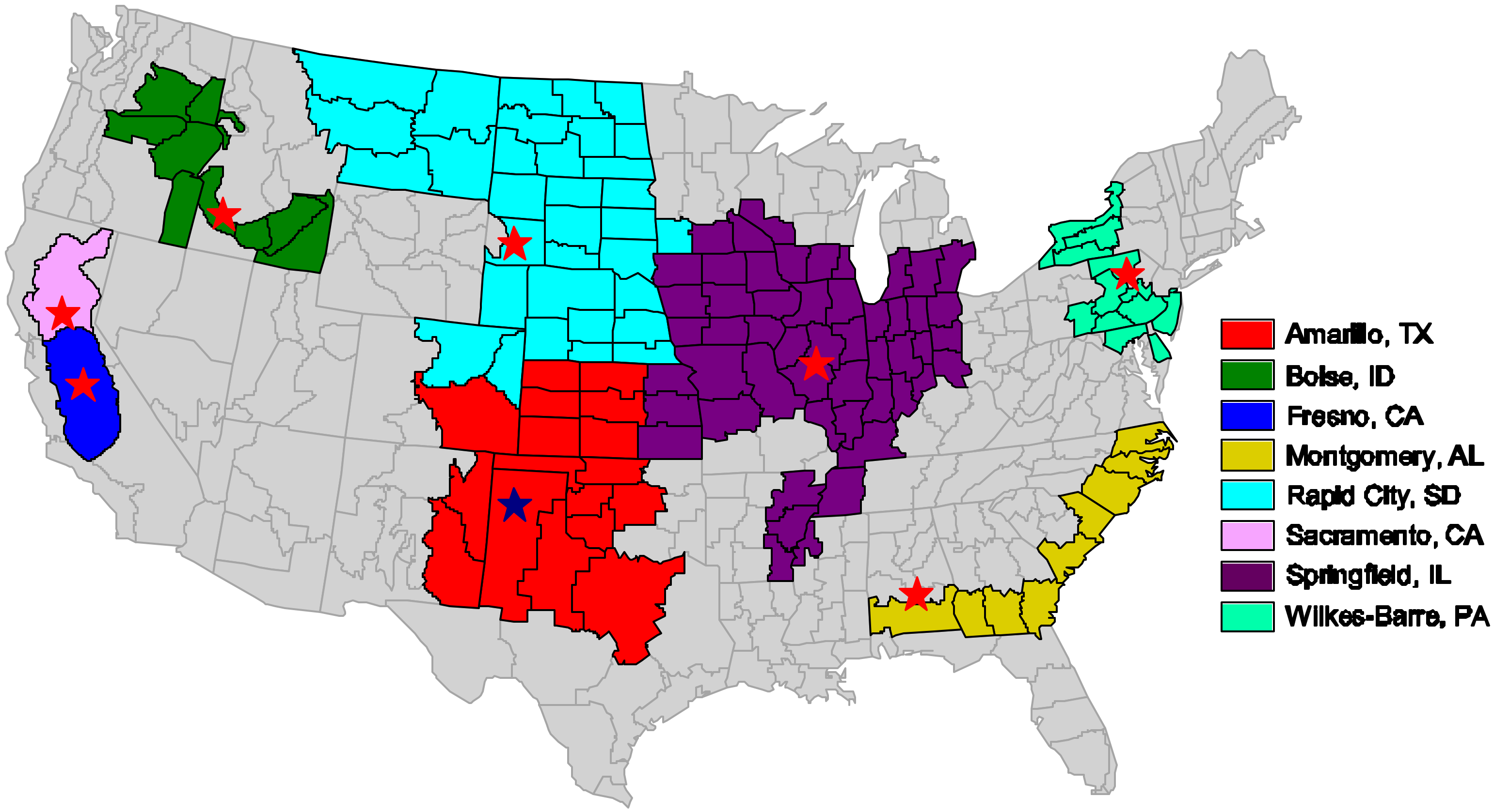


Figure 3. Climate divisions included in analysis and corresponding base stations for daily stochastic weather generation

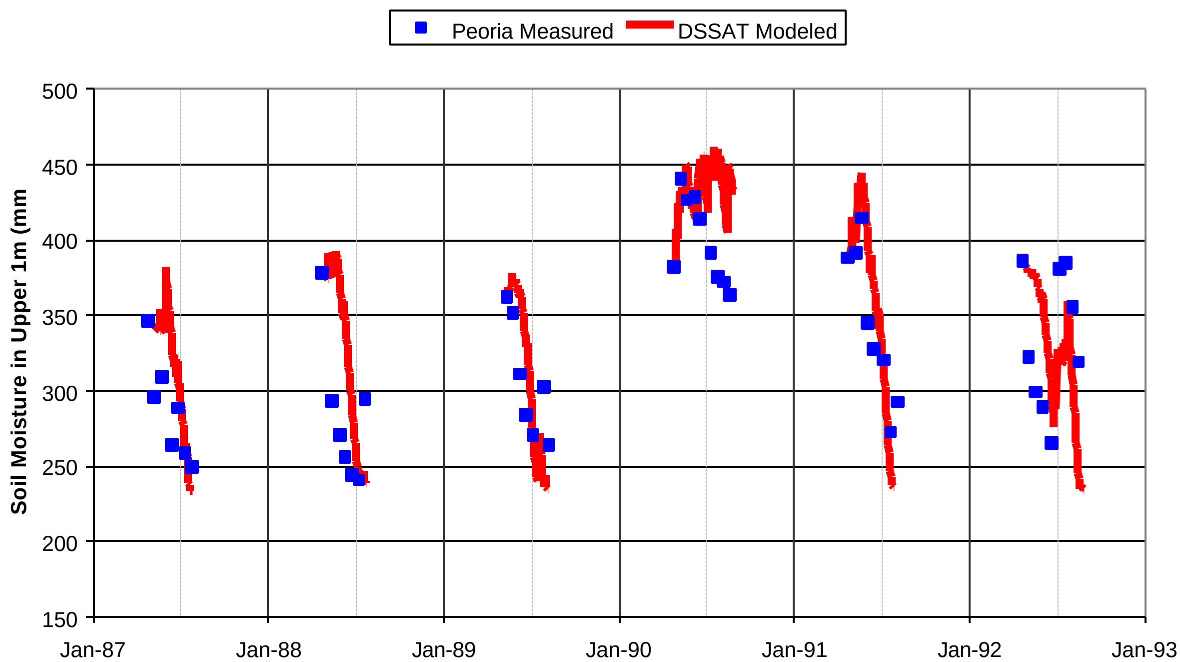


Figure 4. Comparison of Peoria measured and DSSAT modeled soil moisture

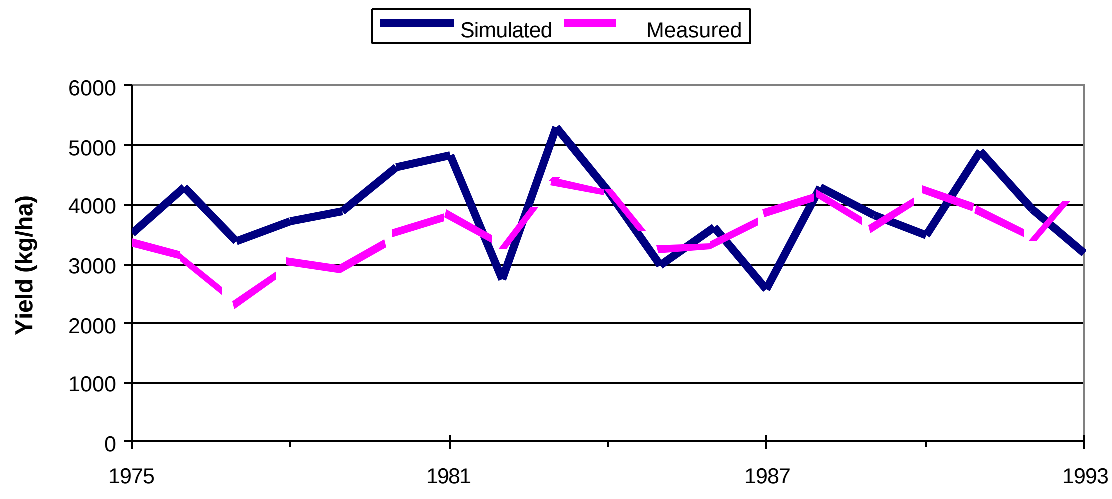


Figure 5a. Calibration results for winter wheat at WA_319

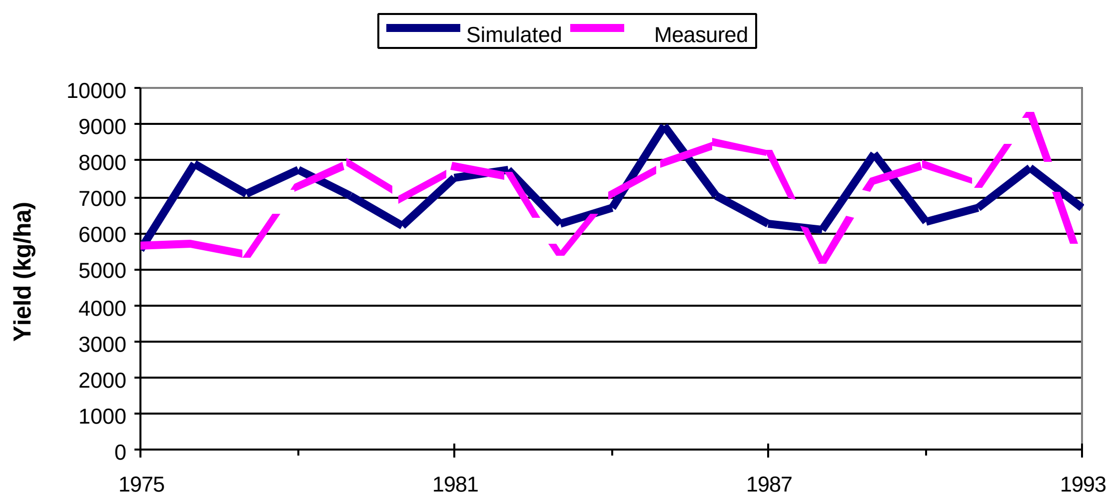


Figure 5b. Calibration results for corn at IA_88

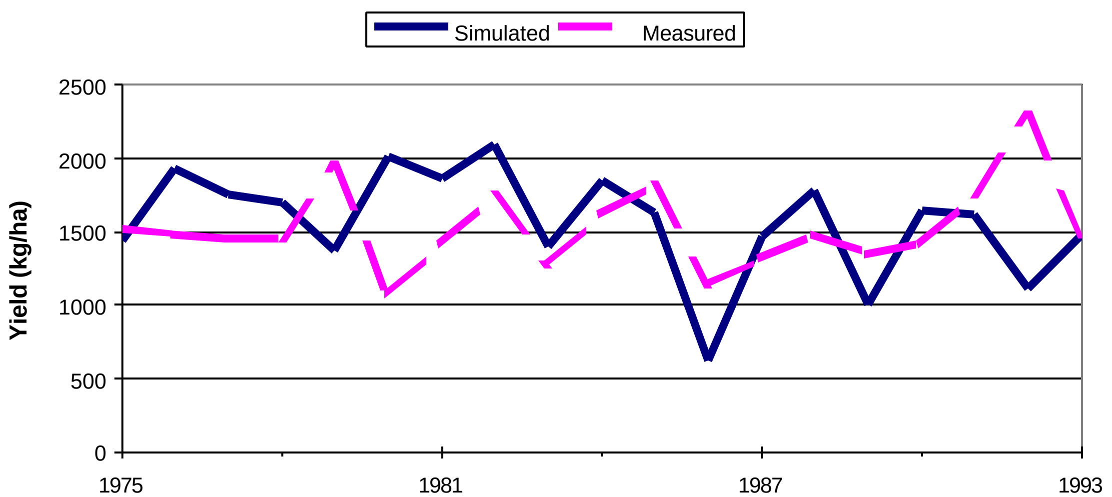


Figure 5c. Calibration results for soybeans at MS_150

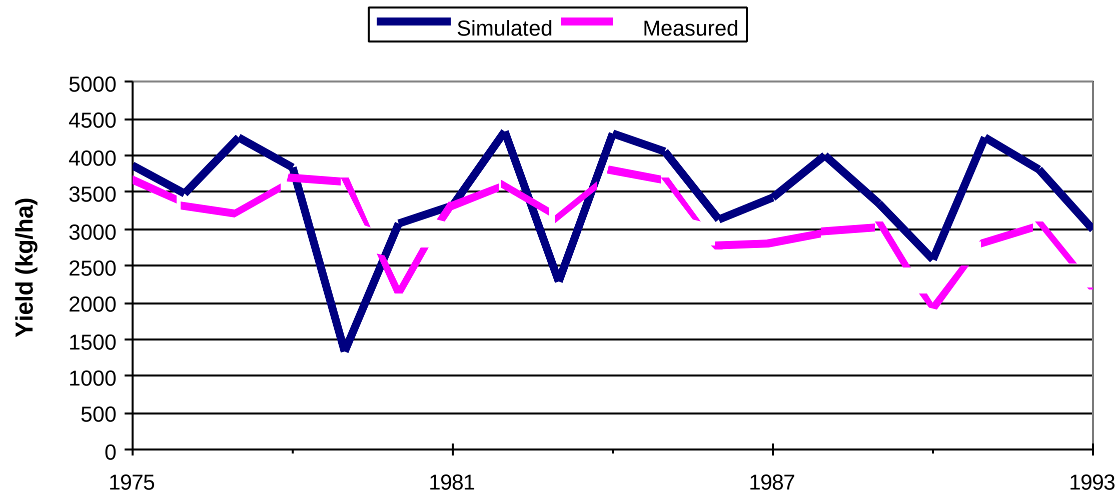


Figure 5d. Calibration results for peanuts at GA_55

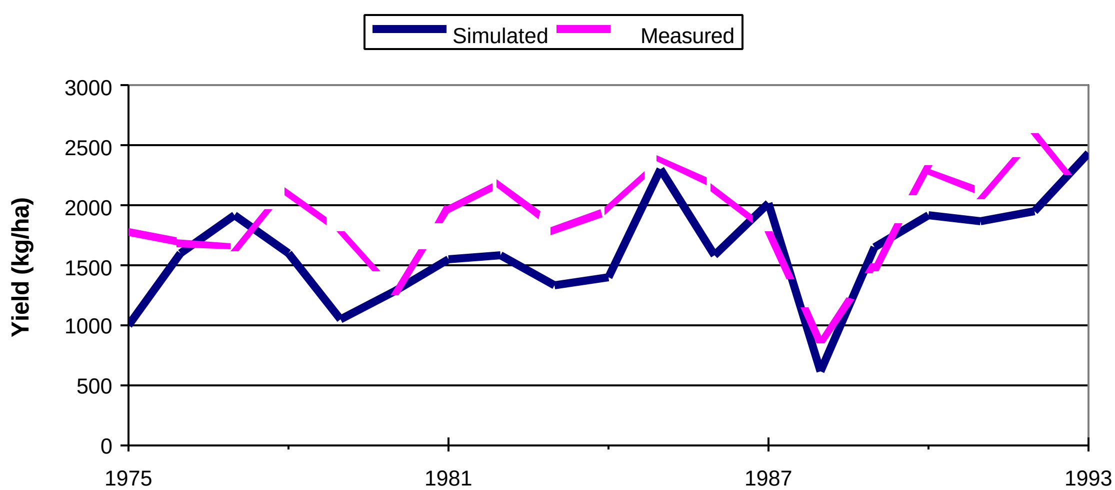


Figure 5e. Calibration results for durum wheat at ND_216

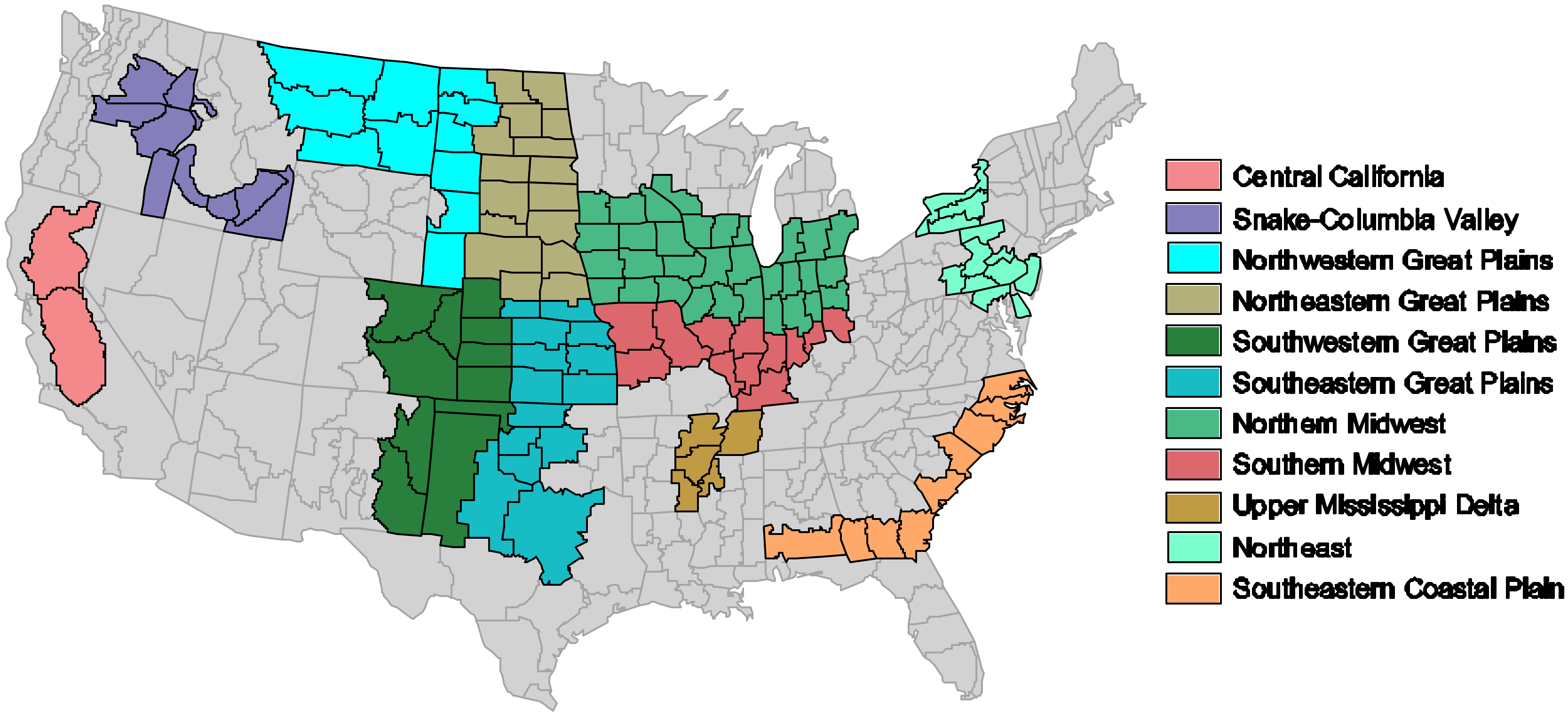


Figure 6. Geographic regions presented in summary tables

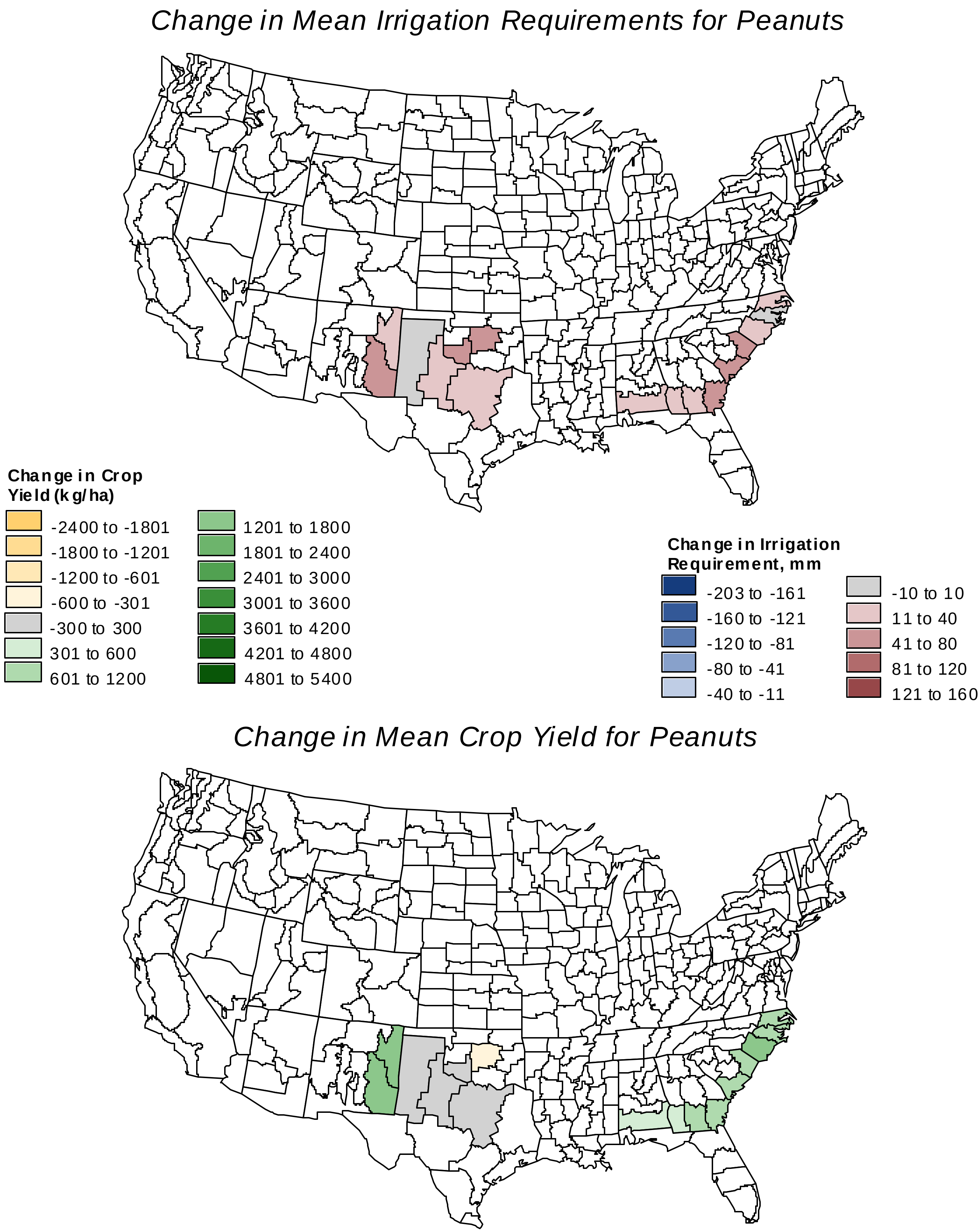


Figure 7. Changes in mean peanut irrigation requirements and crop yield

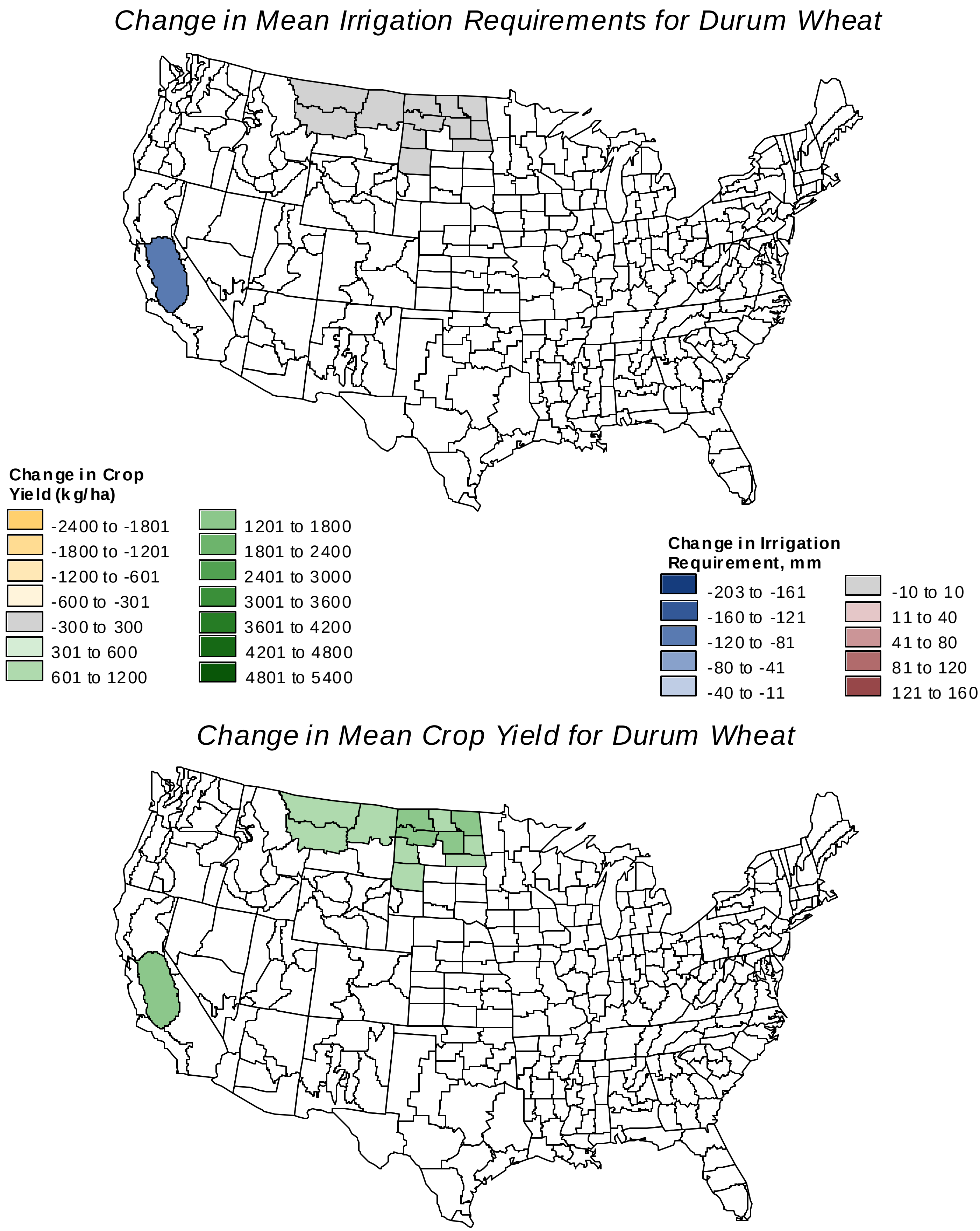


Figure 8. Changes in mean durum wheat irrigation requirements and crop yield

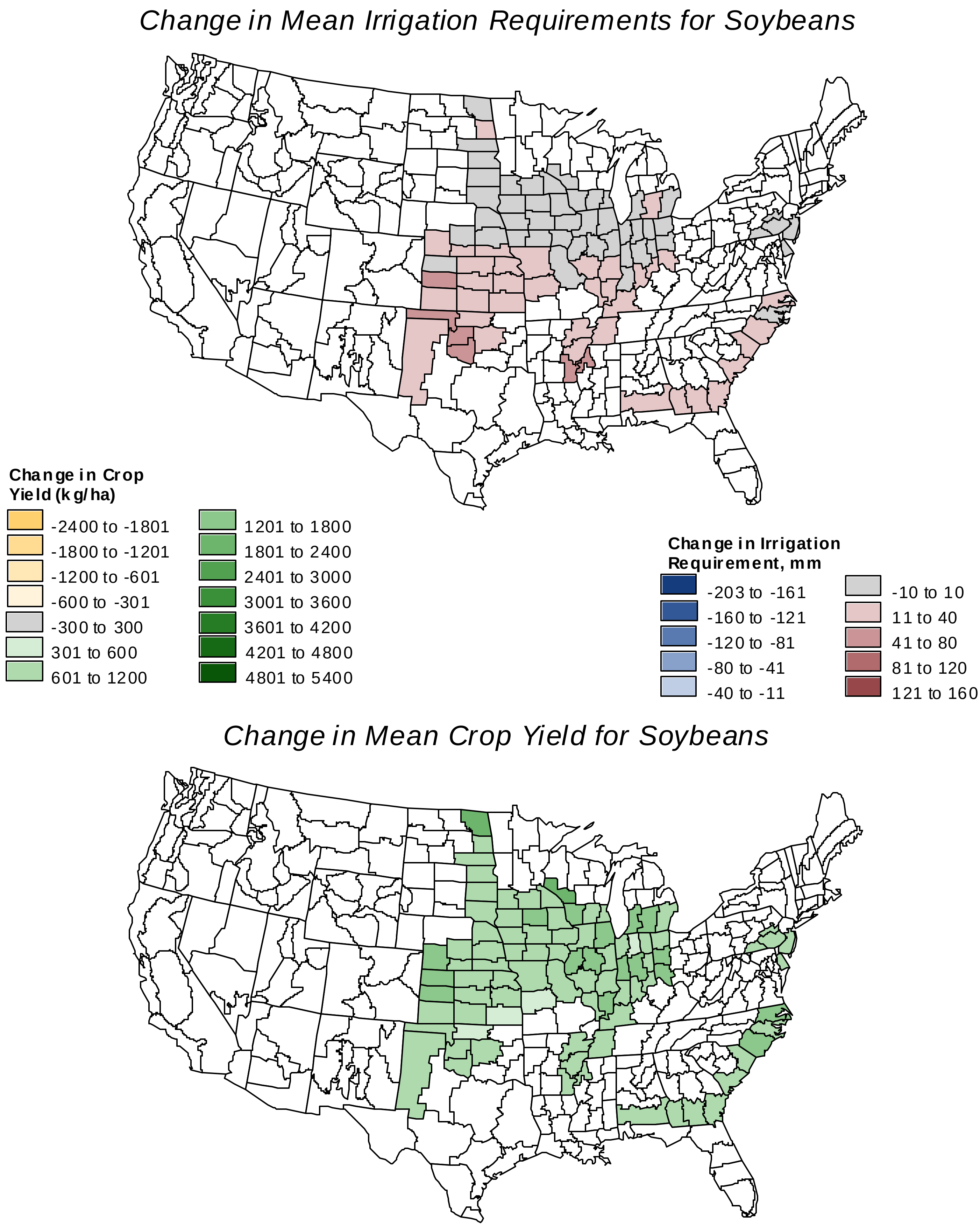
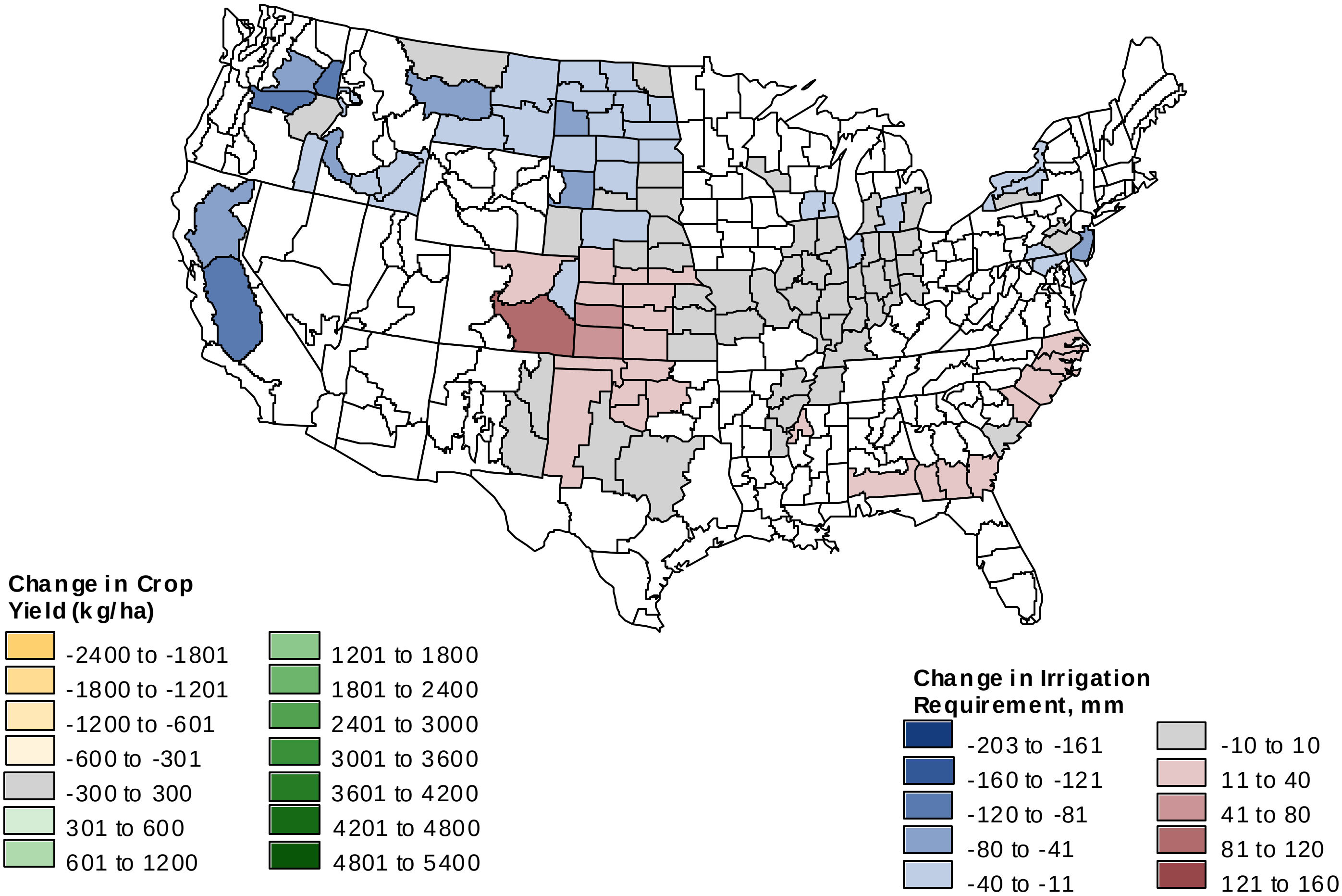


Figure 9. Changes in mean soybean irrigation requirements and crop yield

Change in Mean Irrigation Requirements for Winter Wheat



Change in Mean Crop Yield for Winter Wheat

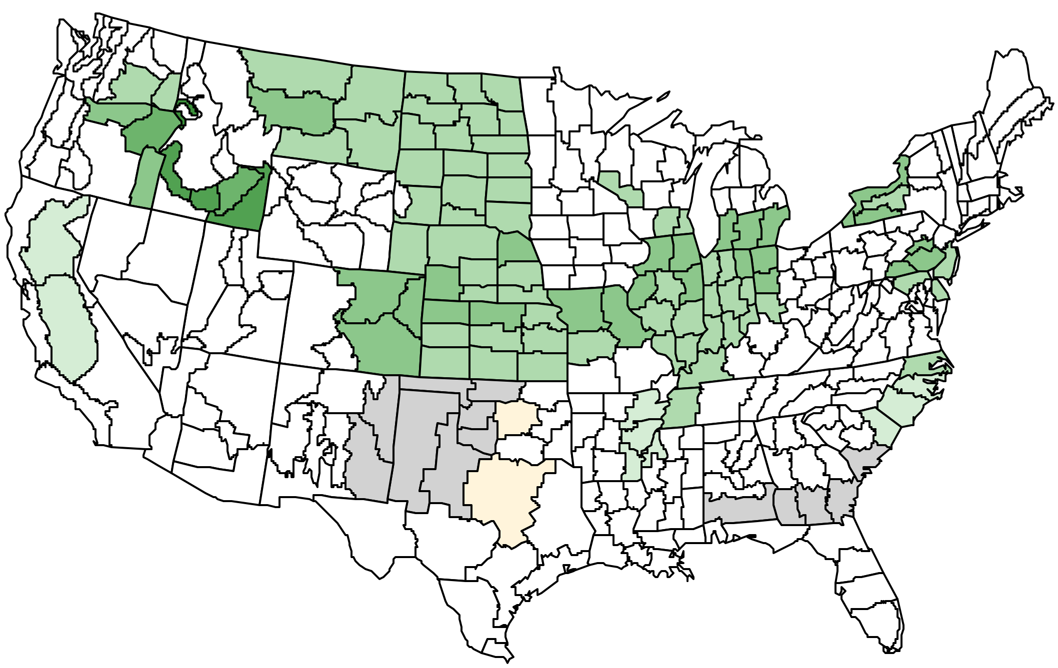


Figure 10. Changes in mean winter wheat irrigation requirements and crop yield

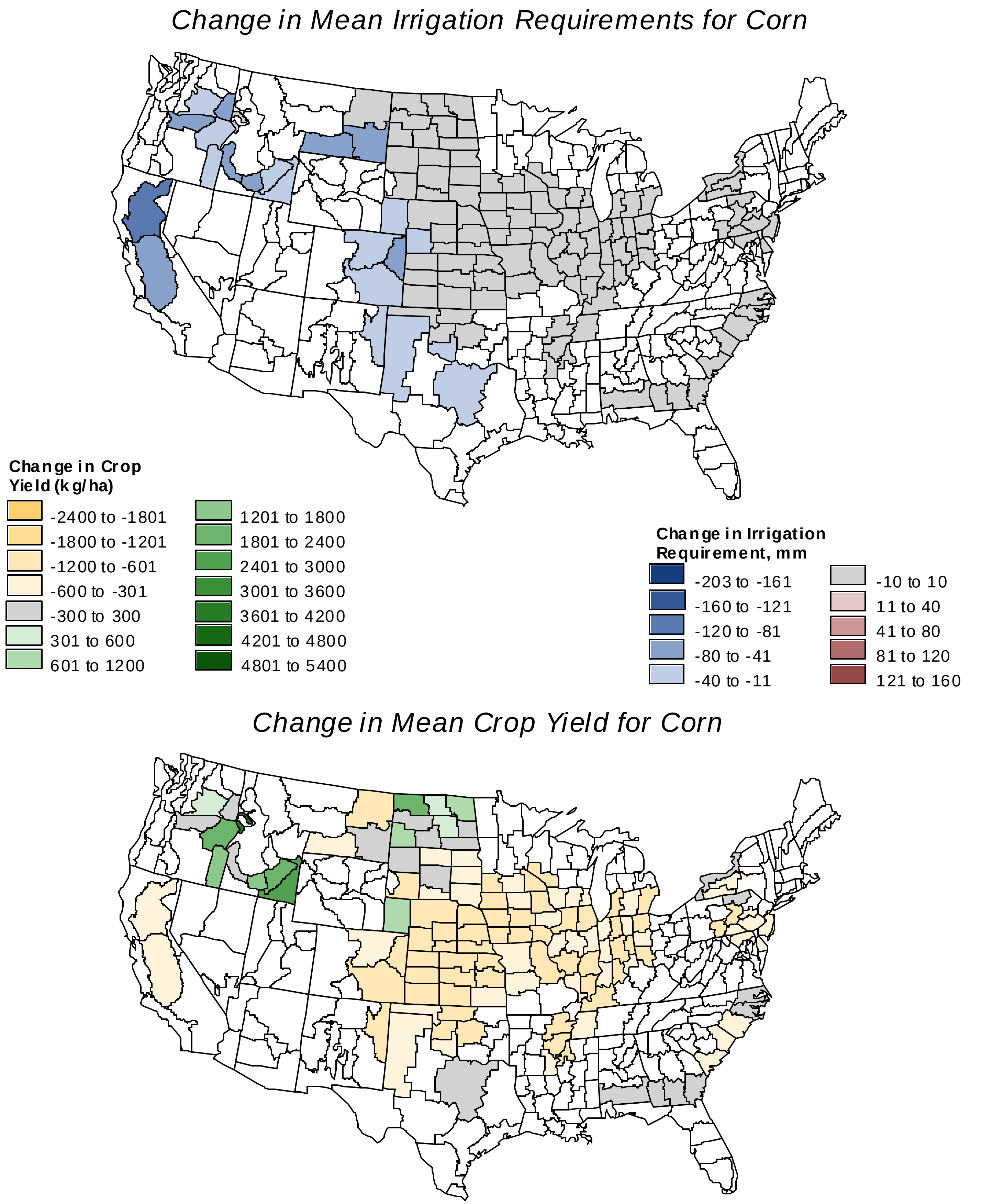


Figure 11. Changes in mean corn irrigation requirements and crop yield

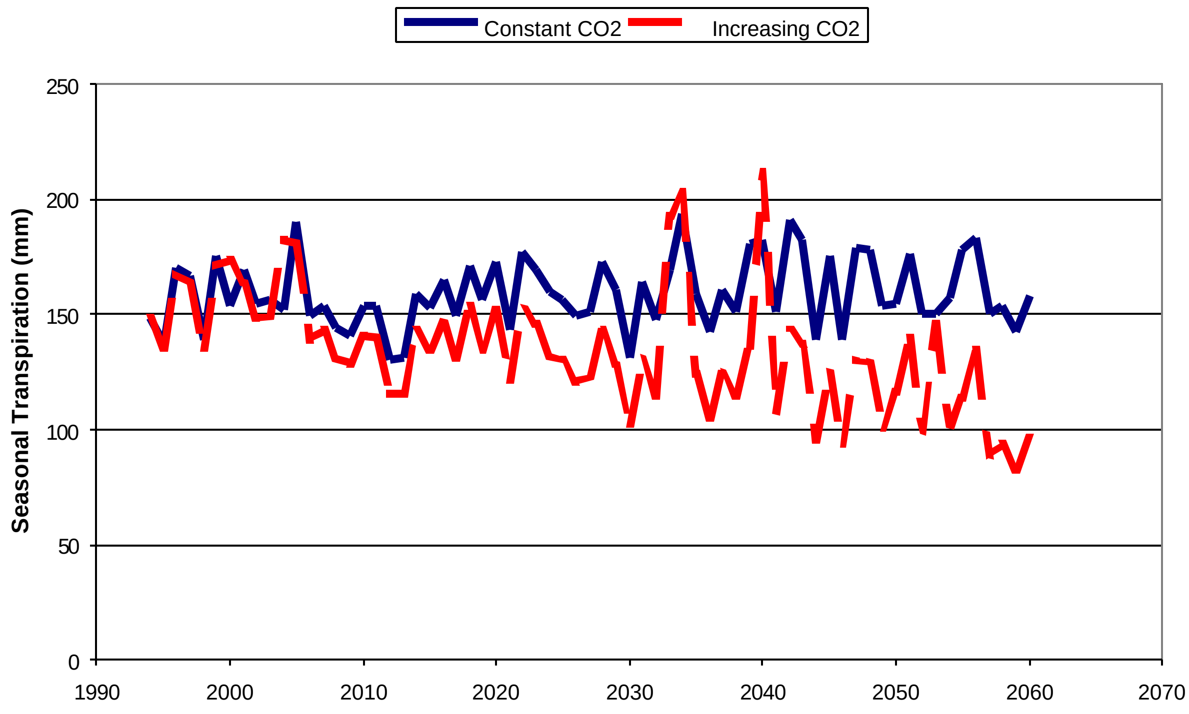


Figure 12. Increasing CO2 effects on corn transpiration

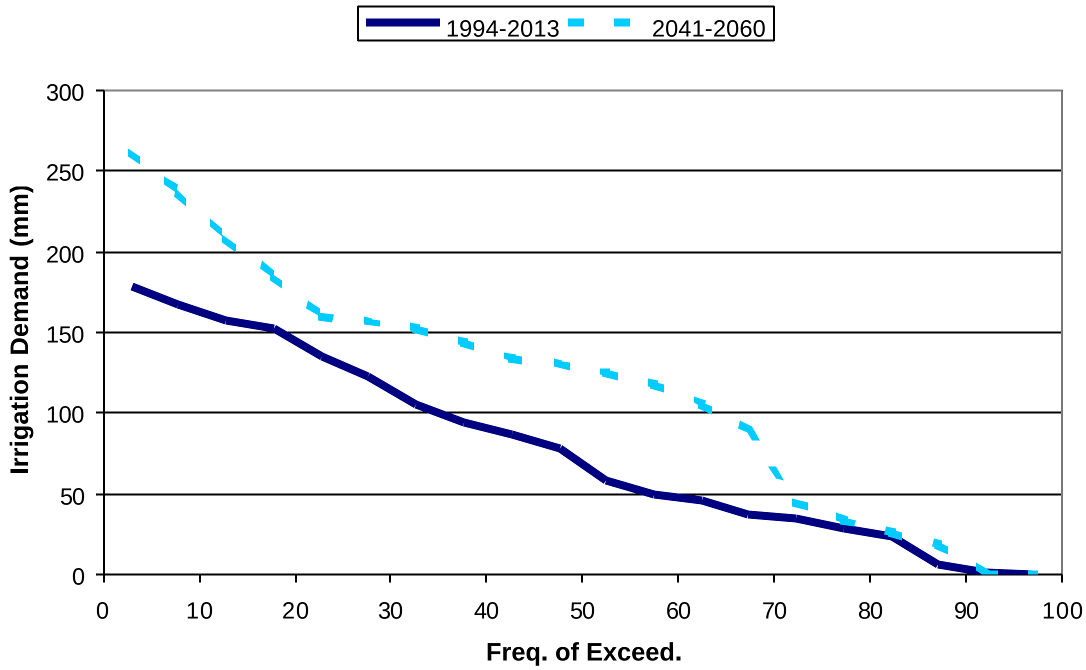


Figure 13a. Change in frequency distribution of irrigation demands, peanuts at SW Georgia, CGCM1 scenario

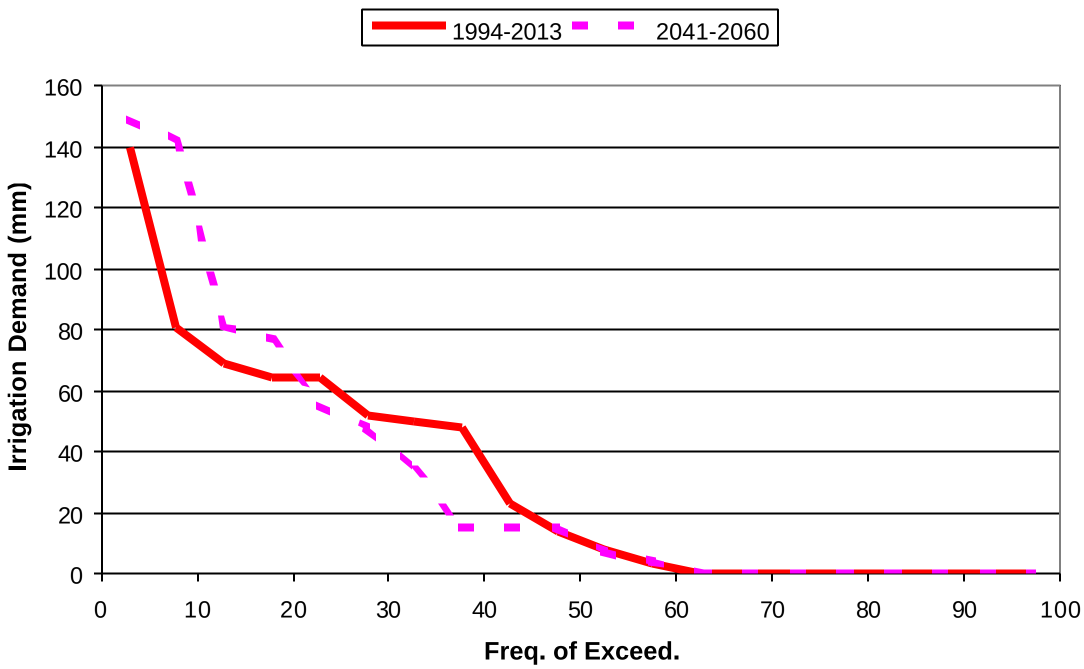


Figure 13b. Change in frequency distribution of irrigation demands, peanuts at SW Georgia, Hadley scenario

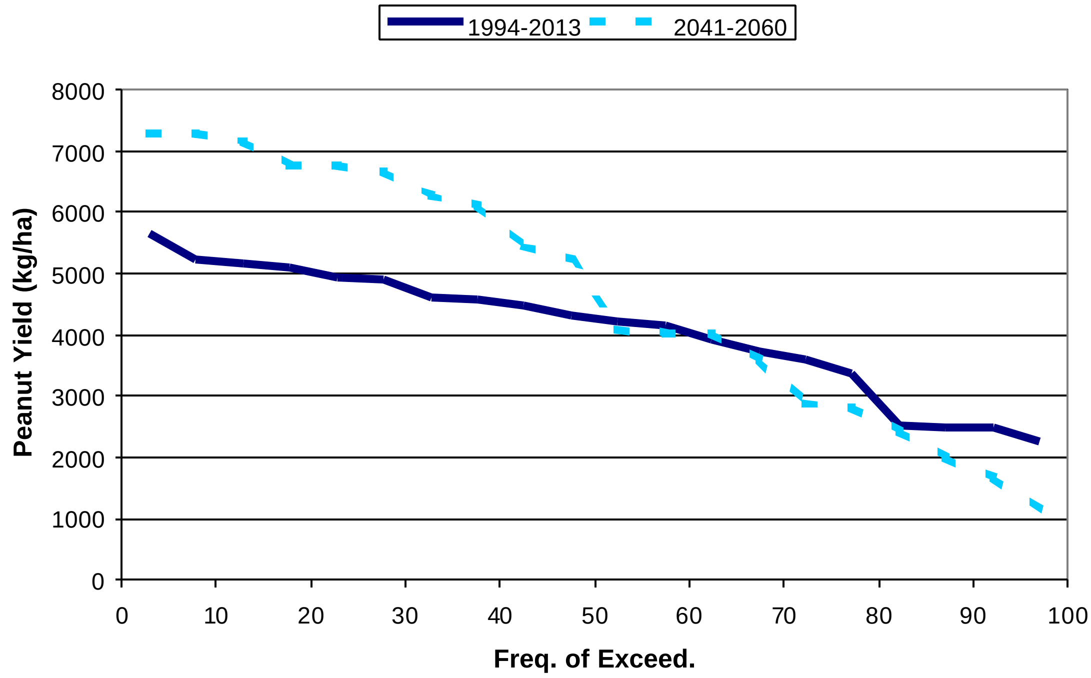


Figure 14a. Change in frequency distribution of crop yield, peanuts at SW Georgia, CGCM1 scenario

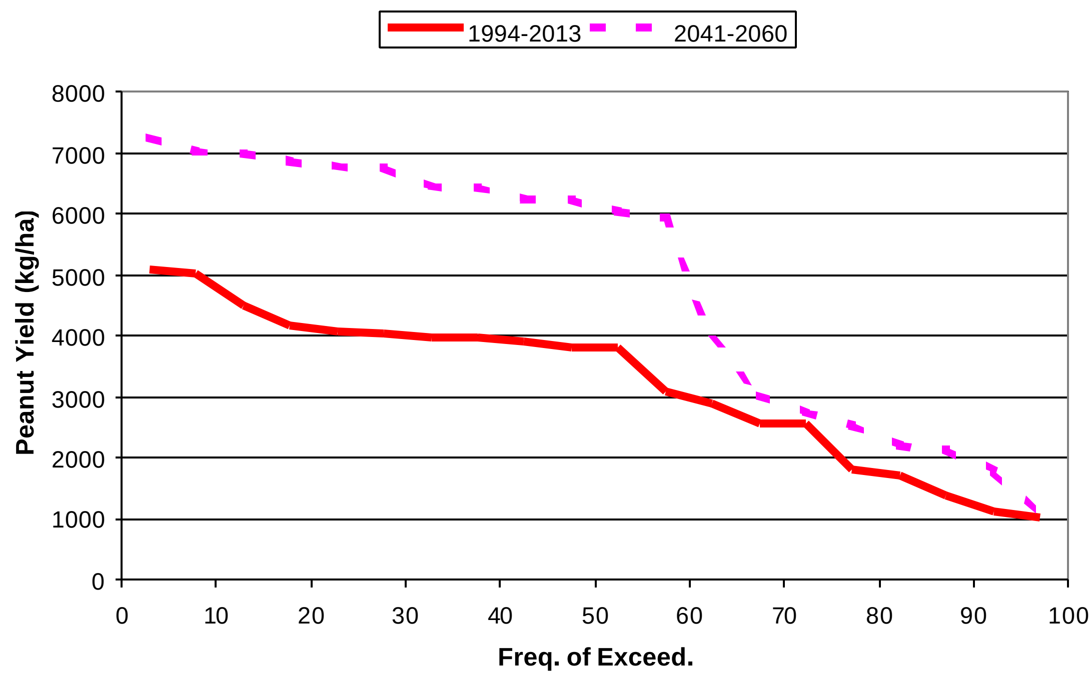


Figure 14b. Change in frequency distribution of crop yield, peanuts at SW Georgia, Hadley scenario

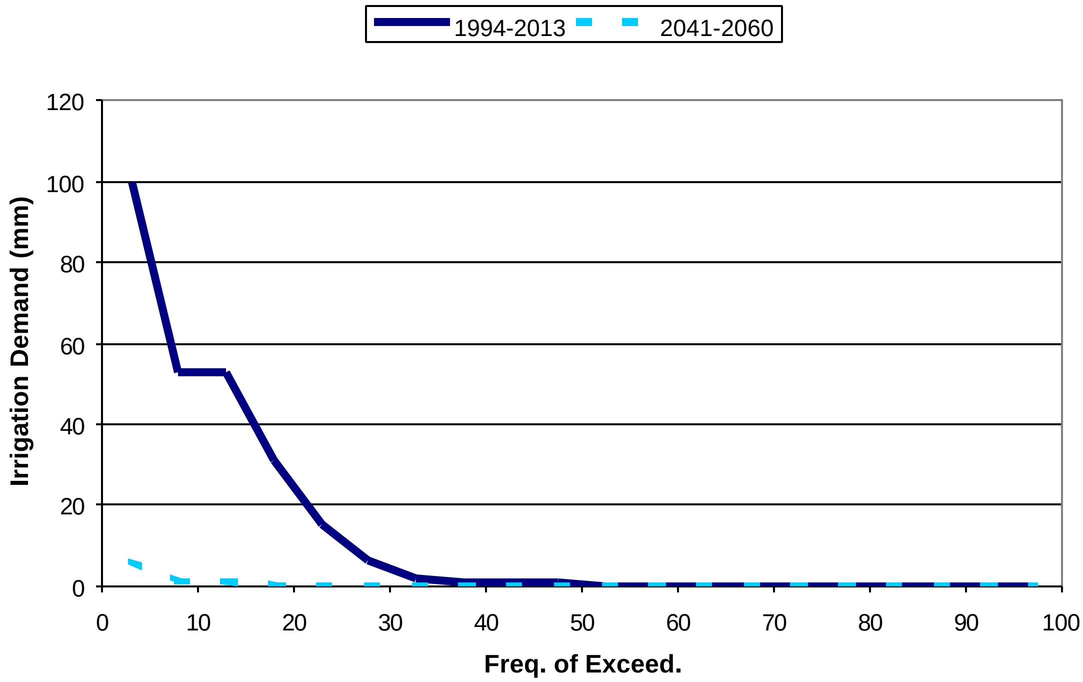


Figure 15a. Change in frequency distribution of irrigation demands, corn at SW Georgia, CGCM1 scenario

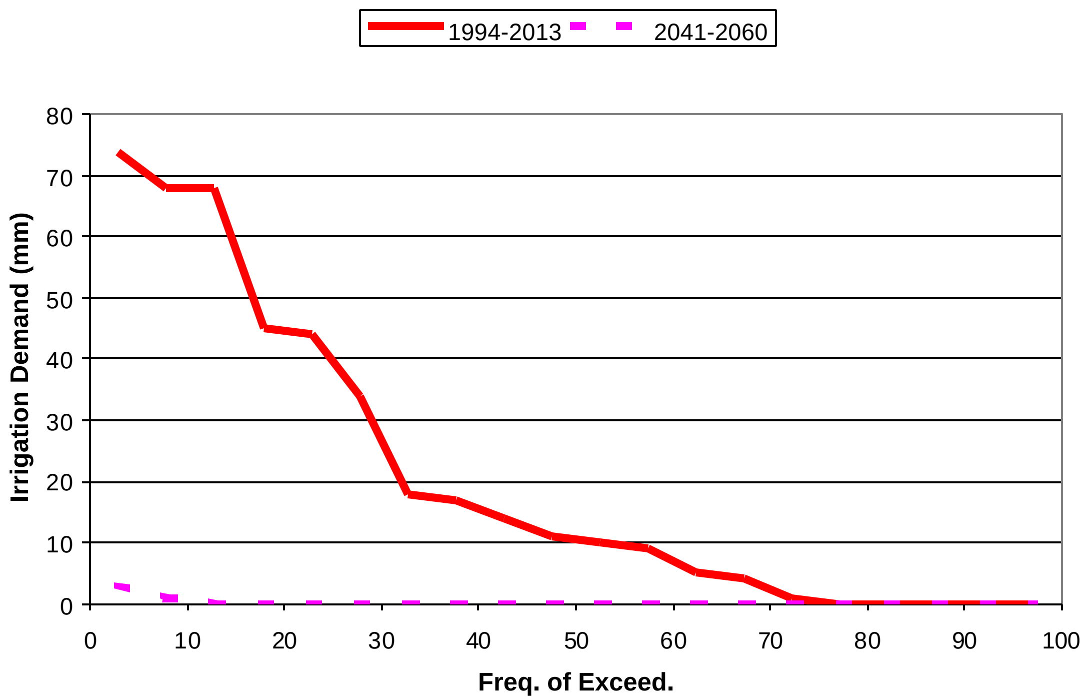


Figure 15b. Change in frequency distribution of irrigation demands, corn at SW Georgia, Hadley scenario

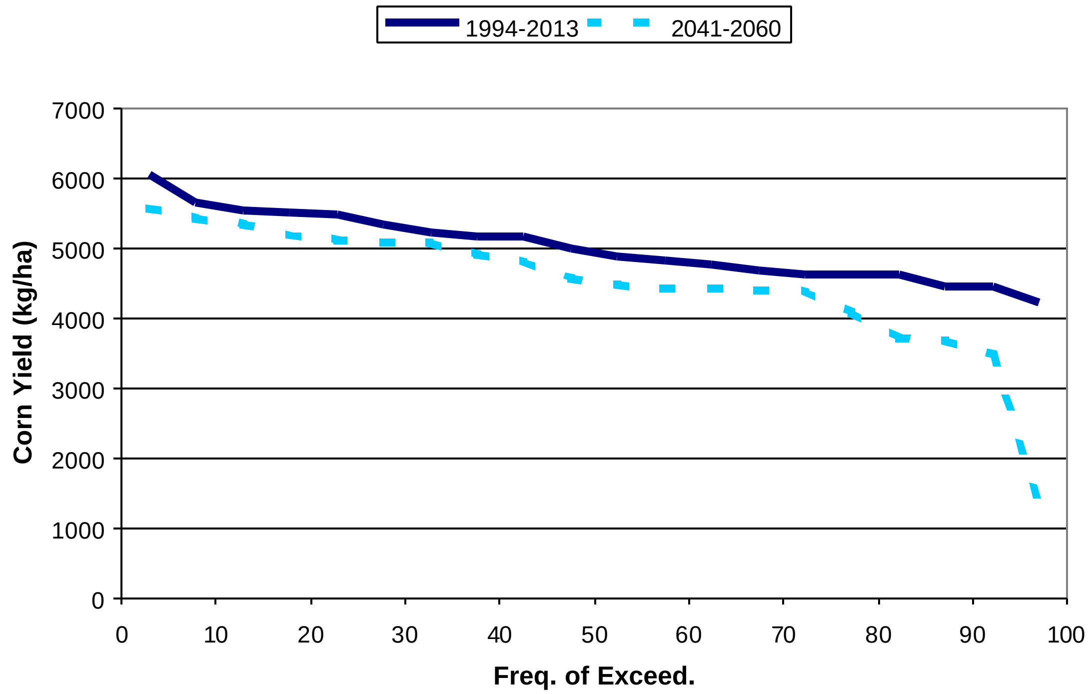


Figure 16a. Change in frequency distribution of crop yield, corn at SW Georgia, CGCM1 scenario

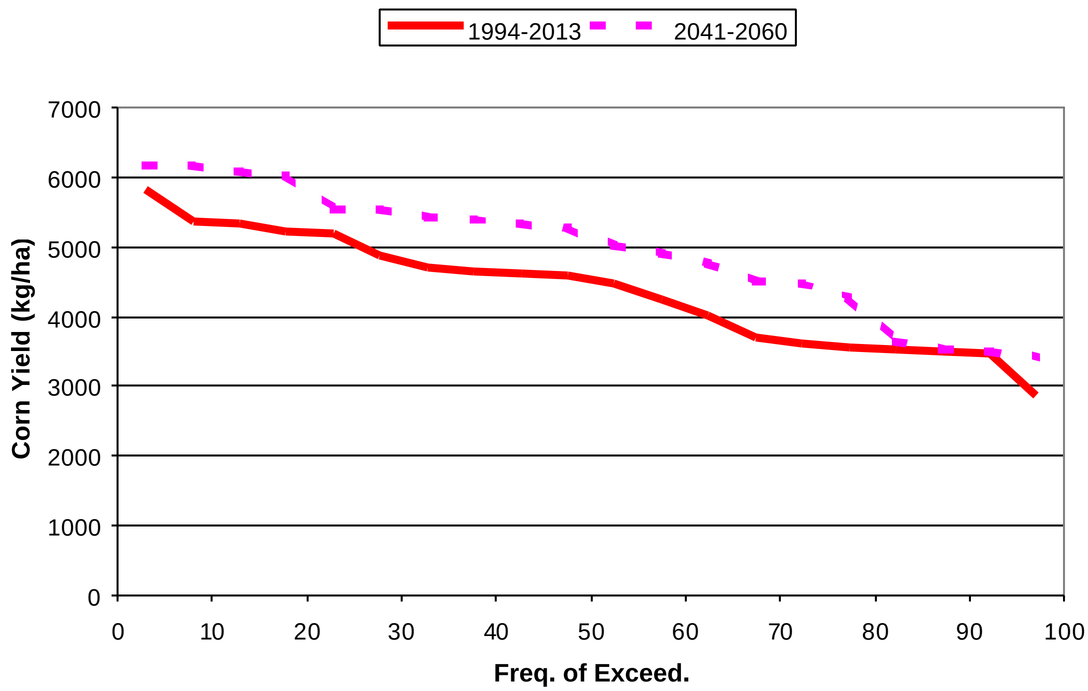


Figure 16b. Change in frequency distribution of crop yield, corn at SW Georgia, Hadley scenario

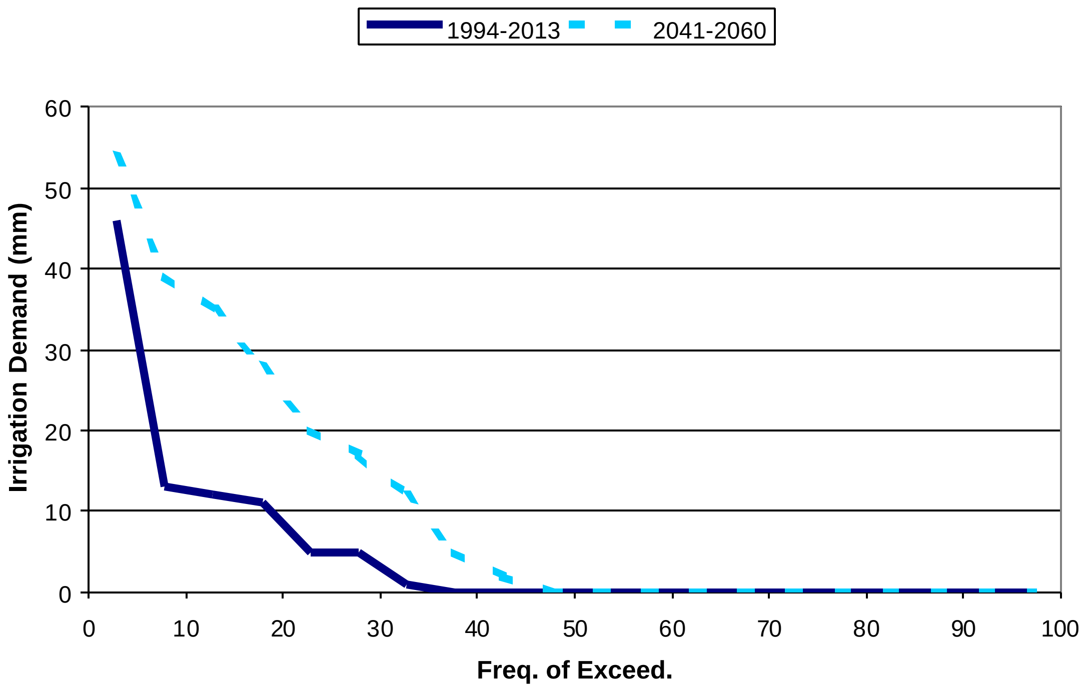


Figure 17a. Change in frequency distribution of irrigation demands, winter wheat at SW Georgia, CGCM1 scenario

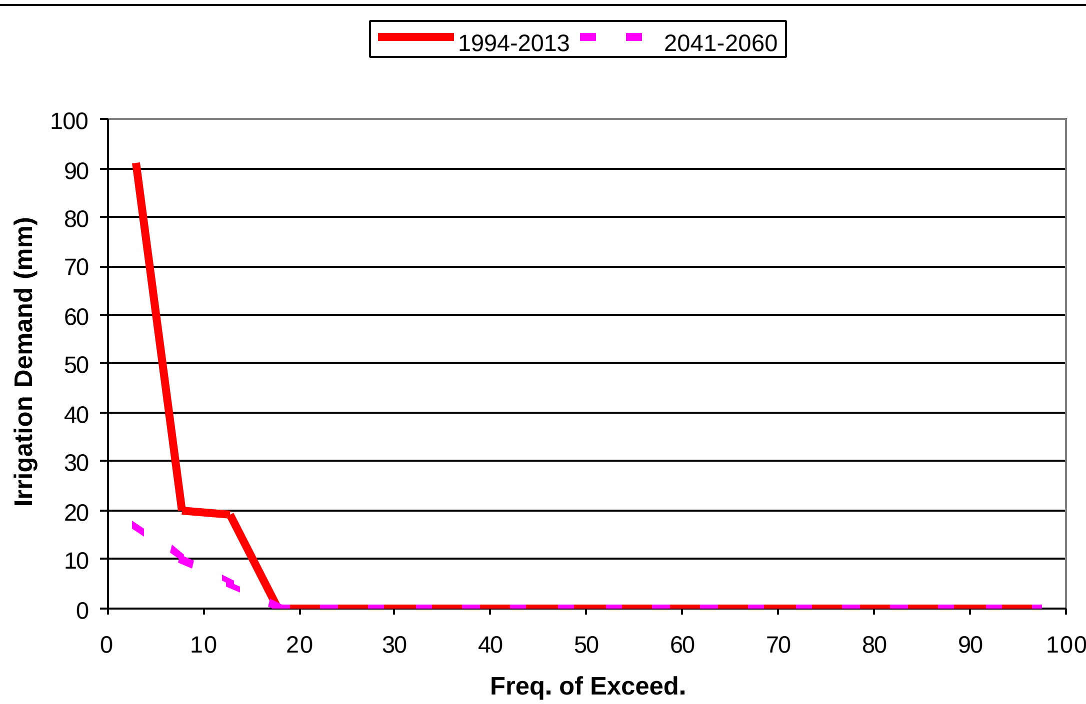


Figure 17b. Change in frequency distribution of irrigation demands, winter wheat at SW Georgia, Hadley scenario

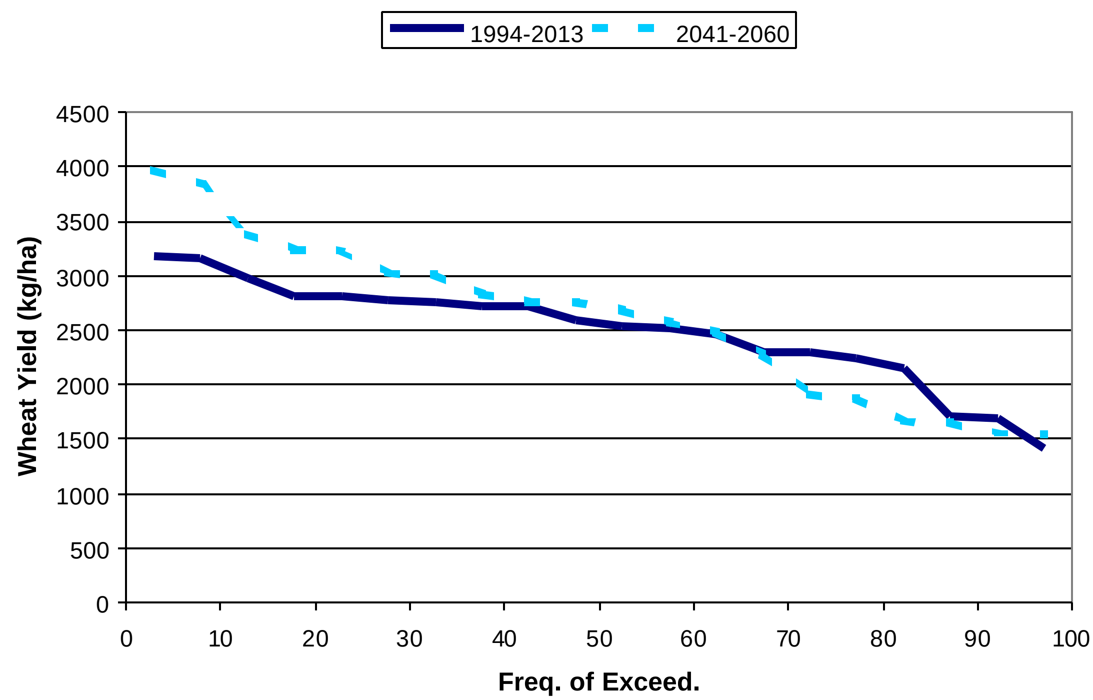


Figure 18a. Change in frequency distribution of crop yield, winter wheat at SW Georgia, CGCM1 scenario

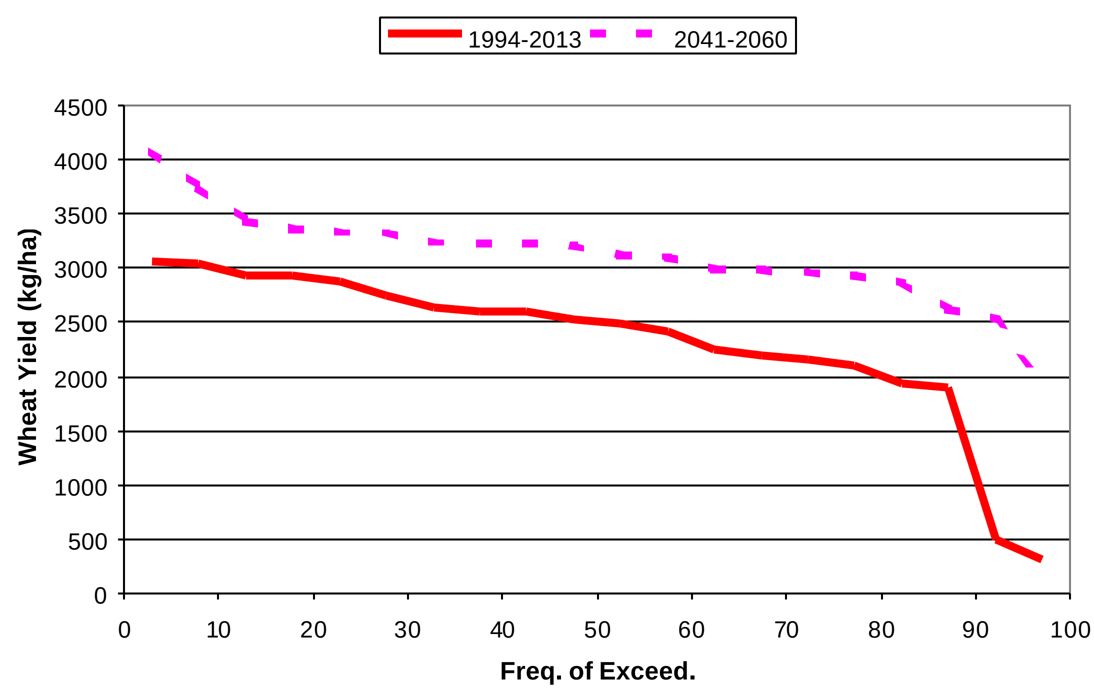


Figure 18b. Change in frequency distribution of crop yield, winter wheat at SW Georgia, Hadley scenario

Table 1a. Regional Mean Changes in Mean Irrigation Requirements [mm (% change)].

	Peanuts	Durum Wheat	Soybeans	Winter Wheat	Corn
Central California		-96.4 (-82%)		-91.6 (-62%)	-74.5 (-44%)
Snake-Columbia Valley				-44.3 (-27%)	-30.6 (-40%)
Northwestern Great Plains		0		-25.9 (-39%)	-15.1 (-75%)
Northeastern Great Plains		2.1 (130%*)	2.5 (31%)	-16.0 (-49%)	-0.8 (-100%*)
Southwestern Great Plains	21.4 (22%)		30.6 (86%)	28.1 (22%)	-15.7 (-50%)
Southeastern Great Plains	31.3 (51%)		23.9 (156%)	16.1 (56%)	-4.0 (-43%)
Northern Midwest			1.6 (18%)	-5.5 (-48%)	-0.2 (-100%*)
Southern Midwest			13.4 (148%*)	-1.3 (-29%)	-0.3 (-87%)
Upper Mississippi Delta			38.8 (137%)	3.7 (180%*)	-2.1 (-54%)
Northeast			0.3 (6%)	-16.9 (-74%)	-0.3 (-100%*)
Southeastern Coastal Plain	29.4 (96%)		18.1 (158%)	15.7 (75%)	-0.7 (-21%)

* Percentage may appear to be very large due to low value of irrigation requirement (< 10 mm) for the initial period.

Table 1b. Regional Mean Changes in Mean Crop Yields [kg/ha (% change)].

	Peanuts	Durum Wheat	Soybeans	Winter Wheat	Corn
Central California		1248 (19%)		423 (9%)	-422 (-4%)
Snake-Columbia Valley				1989 (45%)	1405 (36%)
Northwestern Great Plains		990 (49%)		1106 (44%)	123 (2%)
Northeastern Great Plains		1077 (59%)	1045 (49%)	968 (37%)	-237 (-4%)
Southwestern Great Plains	914 (37%)		1141 (55%)	857 (33%)	-720 (-9%)
Southeastern Great Plains	-44 (-2%)		783 (43%)	456 (16%)	-771 (-12%)
Northern Midwest			1057 (42%)	1131 (34%)	-627 (-10%)
Southern Midwest			1000 (42%)	919 (27%)	-604 (-11%)
Upper Mississippi Delta			896 (50%)	461 (16%)	-630 (-12%)
Northeast			897 (43%)	1177 (33%)	-434 (-8%)
Southeastern Coastal Plain	821 (27%)		1002 (55%)	258 (8%)	-223 (-5%)

Table 1c. Regional Mean Changes in Ninetieth Percentile Irrigation Requirements (mm) and Change-in-Variability Statistic (in brackets).

	Peanuts	Durum Wheat	Soybeans	Winter Wheat	Corn
Central California		-98.0 [*0.96*]		-119.0 [*0.66*]	-74.0 [1.01]
Snake-Columbia Valley				-50.9 [*0.85*]	-40.9 [*0.79*]
Northwestern Great Plains		-0.4 [*0.86*]		-46.5 [*0.64*]	-29.0 [*0.39*]
Northeastern Great Plains		-3.8 [1.54]	6.8 [1.31]	-26.2 [*0.69*]	-1.8 [*0*]
Southwestern Great Plains	8.3 [*0.74*]		48.0 [1.44]	17.0 [*0.80*]	-26.7 [*0.67*]
Southeastern Great Plains	27.5 [*0.92*]		55.4 [2.19]	21.8 [1.19]	-10.8 [*0.43*]
Northern Midwest			5.4 [1.21]	-9.5 [*0.78*]	-0.2 [*0*]
Southern Midwest			50.0 [3.84]	-0.3 [1.31]	-0.1 [*0.18*]
Upper Mississippi Delta			90.0 [2.32]	9.4 [3.67]	-9.4 [*0*]
Northeast			14.0 [2.64]	-36.7 [*0.38*]	-0.7 [*0*]
Southeastern Coastal Plain	45.0 [1.33]		53.9 [2.96]	26.2 [1.38]	-5.8 [*0.43*]

Values in brackets greater than one indicate increasing variability (underlined); values less than one indicate decreasing variability (italicized).

Table 1d. Regional Mean Changes in Tenth Percentile Crop Yields (kg/ha) and Ratio of Change-in-Variability Statistic (in brackets).

	Peanuts	Durum Wheat	Soybeans	Winter Wheat	Corn
Central California		565 [2.01]		226 [1.38]	-345 [*0.89*]
Snake-Columbia Valley				1885 [1.12]	1706 [*0.87*]
Northwestern Great Plains		931 [1.10]		1140 [*0.95*]	434 [*0.71*]
Northeastern Great Plains		761 [1.47]	800 [1.45]	951 [1.02]	37 [*0.68*]
Southwestern Great Plains	681 [1.20]		787 [1.84]	918 [*0.92*]	-530 [*0.78*]
Southeastern Great Plains	57 [*0.90*]		465 [1.70]	430 [1.04]	-872 [1.14]
Northern Midwest			739 [1.41]	1134 [1.00]	-511 [*0.86*]
Southern Midwest			529 [1.63]	895 [1.03]	-538 [*0.92*]
Upper Mississippi Delta			323 [1.80]	404 [1.12]	-1041 [1.42]
Northeast			804 [1.13]	1076 [1.18]	-417 [*0.97*]
Southeastern Coastal Plain	193 [1.40]		732 [1.40]	163 [1.17]	-240 [1.03]

Values in brackets greater than one indicate increasing variability (underlined); values less than one indicate decreasing variability (italicized).

Table 2. Comparison of Assessment Results for Southwest Georgia Under Two Different Climate Scenarios.

		CGCM1		HadCM2	
		Mean	Extreme*	Mean	Extreme*
Peanuts	Change in Irrigation Demand	37 mm	51 mm	-4 mm	12 mm
	Change in Crop Yield	723 kg/ha	-496 kg/ha	1758 kg/ha	754 kg/ha
Corn	Change in Irrigation Demand	-12 mm	-52 mm	-21 mm	-68 mm
	Change in Crop Yield	-573 kg/ha	-771 kg/ha	609 kg/ha	38 kg/ha
Winter Wheat	Change in Irrigation Demand	6 mm	23 mm	-5 mm	-14 mm
	Change in Crop Yield	124 kg/ha	-47 kg/ha	803 kg/ha	720 kg/ha

* Extreme values are ninetieth percentile values for irrigation demand and tenth percentile values for crop yield.