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John Antle
Oregon State University

Keith Paustian
Colorado State University

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John Antle,[a] Susan Capalbo,[b] Edward Elliott,[c] and Keith Paustian[d]

[a, b] *Department of Agricultural Economics and Economics, Montana State University*

[c] *School of Natural Resource Sciences, University of Nebraska*

[d] *Department of Soil and Crop Sciences and Natural Resource Ecology Laboratory*
Colorado State University

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John M. Antle and Susan M. Capalbo
Department of Agricultural Economics and Economics
Montana State University

Edward T. Elliott
School of Natural Resource Sciences
University of Nebraska

Keith H. Paustian
Natural Resource Ecology Laboratory
Colorado State University

July 2003

Corresponding author: John M. Antle
Department of Agricultural Economics and Economics
Montana State University
PO Box 172920
Bozeman MT 59717-2920
Phone: 406 994-3706
Fax: 406 994-4838
E-mail: jantle@montana.edu

Adaptation, Spatial Heterogeneity, and the Vulnerability of Agricultural Systems to Climate Change: An Integrated Assessment Approach

Abstract

In this paper we develop economic measures of vulnerability to climate change with and without adaptation in agricultural production systems. We implement these measures using coupled, site-specific ecosystem and economic simulation models. This modeling approach has two key features needed to study the response of agricultural production systems to climate change: it represents adaptation as an endogenous, non-marginal economic response to climate change; and it provides the capability to represent the spatial variability in bio-physical and economic conditions that interact with adaptive responses. We apply this approach to the dryland grain production systems of the Northern Plains region of the United States. The results support the hypothesis that the most adverse impacts on net returns distributions tend to occur in the areas with the poorest resource endowments and when mitigating effects of CO_2 fertilization and adaptation are absent. We find that relative and absolute measures of vulnerability depend on complex interactions between climate change, CO_2 level, adaptation, and economic conditions such as relative output prices. The relationship between relative vulnerability and resource endowments varies with assumptions about climate change, adaptation, and economic conditions. Vulnerability measured with respect to an absolute threshold is inversely related to resource endowments in all cases investigated.

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1. Introduction

According to the Intergovernmental Panel on Climate Change, vulnerability "…is the extent to which climate change may damage or harm a system; it is a function of both sensitivity to climate and the ability to adapt to new conditions." (IPCC, 1996, p. 5). In its recent report on vulnerability to climate change, the Intergovernmental Panel on Climate Change states, "those with the least resources have the least capacity to adapt and are the most vulnerable" (IPCC, 2001, p. 7). The IPCC also identifies research priorities for assessing vulnerability and adaptation to climate change, and concludes: "Procedures for assessing regional and local vulnerability and long-term adaptation strategies require high-resolution assessments, methodologies to link scales, and dynamic modeling that uses corresponding and new data sets…greater emphasis on the development of methods for assessing vulnerability is required, especially at national and sub-national scales where impacts of climate change are felt and responses are implemented. Methods designed to include adaptation and adaptive capacity explicitly in specific applications must be developed." (IPCC, 2001, p. 22)

Following these recommendations, in this study we use economic concepts to devise several measures of vulnerability to climate change that account for adaptation. We then develop a quantitative method to assess impacts of climate change on agriculture, taking into account adaptation by farmers, as well as the spatial heterogeneity in bio-physical and economic conditions that affect the ability to adapt. Our integrated assessment approach is based on the use of a statistically representative sample of data of individual decision units (farmers' fields), and coupled, spatially explicit ecosystem and economic models. With a statistically representative sample of data from farmers' fields, the models can be simulated to represent the impacts of climate change on the population of economic decision units, and results can be used to represent impacts on the population in statistical terms and can be statistically aggregated for policy analysis. Thus, this approach is able to provide information about changes in vulnerability in response to climate change within heterogeneous populations – information that is not available from analysis based on "representative" individual farm data extrapolated to a region, or from the use of aggregated data. We demonstrate this approach in an analysis of climate change impacts in the dryland, grain-producing region of Montana. Recognizing research that shows the potentially important positive impacts of CO_2 fertilization on crop yields, we analyze the impacts of climate change with both present and elevated CO_2 concentrations (IPCC, 2001, p. 29). Coupled ecosystem and economic models are used to simulate the effects of climate change and CO_2 fertilization on land use and net returns to grain production systems. We use these coupled models to assess vulnerability under different assumptions about adaptation and economic conditions.

In the second section we provide a conceptual framework for economic analysis of agricultural adaptation to climate change. The third section provides a detailed description of the integrated assessment approach. The fourth section applies this approach to investigate the impacts of climate change and CO_2 fertilization in the dryland grain-producing region of Montana, a semi-arid region with a high degree of climate risk associated with variations in temperature and precipitation.

2. Adaptation, Spatial Heterogeneity, and Vulnerability

Figure 1 illustrates our economic analysis of adaptation to climate change and CO_2 fertilization. The function v(x, z, c, p, w) represents the value of an agricultural production system per unit time (say, per year), where x is a vector of management decisions (e.g., input quantities, timing of operations, etc.), z is a vector representing the various forms of capital affecting production (natural capital such as soils, physical capital such as land and machinery, human and social capital), c represents the climate regime (which may include effects of increased CO_2 concentrations), p represents prices of outputs, and w is input prices. Following standard economic theory, we assume these value functions are globally concave with respect to management decisions (x), implying that there is an optimal decision that maximizes the value of the system. Examples of a value function are expected returns above variable cost (used in this study), and expected utility of net returns.

Holding prices constant, an adverse change in climate will reduce the technical potential of a production system, and thus will shift the value function downwards and also may change its position and shape in the space of management decisions (conversely, a favorable change in climate or the positive effects of CO_2 fertilization would shift the value function upwards). Figure 1 illustrates an adverse impact by shifting the value function downwards and toward the origin. With this shift in the value function, the efficient management decision becomes x_1 and the economically efficient manager attains returns of $v(x_1, z_0, c_1, p_0, w_0)$. Changes in climate also may induce changes in aggregate production and prices, in which case the value function would also shift in response to price changes. For brevity we focus our discussion here on changes in technical potential, taking prices as given, but note that a similar analysis applies when there is a change in prices.

A loss from an adverse climate change, or a gain from favorable climate change or CO_2 fertilization, can be measured in absolute or in relative terms. Vulnerability also can be measured in relation to a threshold value (IPCC, 1996; Schimmelpfennig and Yohe, 1999). While the concept of a threshold value of an indicator such as income has intuitive appeal, the concept is not based in decision theory and the specification of a threshold value in an analysis of vulnerability is arbitrary.

A farmer that experiences an adverse change in climate from c_0 to c_1, but who does not change management in response, earns a return of $v(x_0, z_0, c_1, p_0, w_0) < v(x_0, z_0, c_0, p_0, w_0)$. We define the *relative climate vulnerability – no adaptation* of the system as the maximum potential loss relative to the base climate,

$$RCVN = [v(x_0, z_0, c_0, p_0, w_0) - v(x_0, z_0, c_1, p_0, w_0)]/ v(x_0, z_0, c_0, p_0, w_0).$$

Figure 1 shows that with climate change, management decision x_0 is inefficient, and adapting management optimally to x_1 yields a return to the system of $v(x_1, z_0, c_1, p_0, w_0) > v(x_0, z_0, c_1, p_0, w_0)$. We define the loss associated with climate change and optimal adaptation as the *relative climate vulnerability – adaptation* of the system, and we measure it as

$$RCVA = [v(x_0, z_0, c_0, p_0, w_0) - v(x_1, z_0, c_1, p_0, w_0)]/ v(x_0, z_0, c_0, p_0, w_0).$$

Therefore, a manager who does adapt to the changed climate conditions gains the amount $v(x_1, z_0, c_1, p_0, w_0) - v(x_0, z_0, c_1, p_0, w_0)$ relative to the manager who does not adapt. We define the *relative adaptive gain* of the system as

$$RAG = [v(x_1, z_0, c_1, p_0, w_0) - v(x_0, z_0, c_1, p_0, w_0)]/ v(x_0, z_0, c_0, p_0, w_0).$$

We define the vulnerabilities to be positive when there is a loss, and negative where there is a net gain from climate change or CO_2 fertilization, and we define RAG as a non-negative number.

These concepts also could be stated in absolute terms by multiplying them by the base value $v(x_0, z_0, c_0, p_0, w_0)$.

Let an absolute threshold for the value function be a fixed value AT defined in the units of the value function, and let a relative threshold be $0<RT<1$. We define absolute or relative vulnerability, without and with adaptation, as the probability that the value function under a perturbed climate (c_1) would be less than or equal to the absolute or relative threshold:

$$ATCVN = Pr\{v(x_0, z_0, c_1, p_0, w_0) < AT\}$$

$$ATCVA = Pr\{v(x_1, z_0, c_1, p_0, w_0) < AT\}$$

$$RTCVN = Pr\{v(x_0, z_0, c_1, p_0, w_0) < RT \cdot v(x_0, z_0, c_0, p_0, w_0)\}$$

$$RTCVA = Pr\{v(x_1, z_0, c_1, p_0, w_0) < RT \cdot v(x_0, z_0, c_0, p_0, w_0)\}.$$

As discussed by the IPCC (2001), systems with relatively poor endowments of capital (human, social, physical, natural) may be less able to adapt to climate change, and thus more vulnerable, than systems with relatively better endowments. Our analytical framework can be used to investigate the following specific hypotheses:

Hypothesis 1: Adverse changes in Net Returns Distributions are related to Endowments and Adaptation. We can use the statistical distribution of the value function (e.g., net returns in our application below) to characterize the economic status of the population of agricultural producers in a region. Expected returns of the less-well endowed producers should shift towards the origin, implying a lower mean for the population, a greater dispersion of returns within the population, and a more right-skewed distribution of returns. We would also expect these effects to be magnified when farm managers do not adapt to climate change, because while management would not need to be changed on some land units, a large proportion of the population would suffer a substantial loss without adaptation.

Hypothesis 2: Vulnerability is inversely related to adaptation and resource endowments. The relationship between vulnerability and adaptation is a direct consequence of the definitions of vulnerability presented above, because a loss from an adverse climate change without adaptation is necessarily greater than or equal to a loss with adaptation. However, the impact of resource endowments on vulnerability may depend on whether a relative or absolute measure of vulnerability is used. As noted in Hypothesis 1, an adverse climate change should affect a system with a poor resource endowment more than a better-endowed system. Yet, a system with a poorer endowment will have a lower initial value function, so it is possible for the poorly-endowed system to experience a smaller *relative* loss than a better-endowed system, even though it is worse off in absolute terms. However, systems with relatively poor endowments will always be closer to an absolute threshold than those with better endowments. This suggests that while Hypothesis 2 should be true for vulnerability measured against an absolute threshold, it may not be true when measured in relative terms.

Hypothesis 3: The benefits of adaptation are greater for less-well endowed regions. While all farmers in a given region are likely to have access to the same production technology, there is substantial (and well-documented) spatial heterogeneity across land units in most regions of the world in terms of physical characteristics (soils, topography, microclimate) that affect agricultural productivity. Moreover, farmers differ substantially in their human capital endowments (differing abilities, education, and experience) and they utilize various combinations of different types and amounts of physical capital in the production process. If physical and human capital endowments are positively correlated with natural capital endowments, we would expect to see greater adaptive vulnerability, and thus greater gains from adaptation, in regions that have poor natural capital endowments.

3. Modeling Agricultural Impacts of Climate Change: Integrated Assessment Approach

The preceding discussion showed that the magnitude of changes in management needed to adapt to climate change are determined by — or in economists' jargon, are *endogenous to* — the ways that climate affects the production system. We also noted above that spatial heterogeneity is a key feature of agricultural production systems and should play an important role in analysis of adaptation. In this section we provide an overview of the integrated assessment approach used in this study.

Since the early 1990s, there have been various studies of agricultural impacts of climate change (see IPCC, 2001a, section 5.3.4 for an overview). In their review of the literature on climate change impacts on US agriculture, Lewandrowski and Schimmelpfennig (1999) categorize the methods used as a crop response approach or a spatial analogue approach. Various studies have made different assumptions about adaptation, including changes in cultivars, planting and harvest dates, crop mix, and use of irrigation (Kaiser, 1999).

In this section we outline an approach to modeling agricultural impacts of climate change that utilizes certain features of both the crop response approach and the spatial analogue approach. Our approach, like the crop response approach, uses biophysical process models to represent the impact of climate change and CO_2 fertilization on crop production. Like the spatial analogue approach, our approach uses econometric models to represent and simulate farmers' endogenous response to climate change. However, unlike the spatial analog approach, our integrated approach utilizes the process-based information embodied in a biophysical model to simulate the effects of climate and CO_2.

Moreover, our integrated assessment approach differs from other studies in that it utilizes a statistically representative sample of the population of farmer's fields. All other studies utilize either “representative” farm data that are extrapolated to a larger region, or aggregated data. By conducting the integrated simulations for a statistically representative sample of farmers’ fields, our integrated assessment approach provides information about changes in the characteristics of the population in response to climate change that cannot be inferred from “representative” data or aggregated data. Thus, for example, this approach can provide estimates of the proportion of the population that is vulnerable, using the concepts described in the preceding section. Also, by conducting the analysis at the level of the economic decision unit, our integrated assessment approach avoids the problem of aggregation bias that is known to occur with spatially aggregated data (Hansen and Jones, 2000; Antle and Stoorvogel, 2001).

An overview of the integrated assessment approach is presented in Figure 2. The left-hand side of the figure represents the components of the analysis based on the Century model (see Parton et al., 1994; Metherell et al., 1993), and the right-hand side represents the components of the analysis based on the econometric-process simulation model (Antle and Capalbo, 2001). At the top of the figure, the incorporation of spatial heterogeneity is indicated by the use of site-specific bio-physical data and economic data to parameterize and simulate the two models. A key feature of this integrated assessment approach is the focus on the characterization of production systems — i.e., specific combinations of genetic material, physical resources (soils, climate), capital, and management. As we discuss in detail below, site-specific data are used to characterize these production systems for operation of the Century model and for parameterization of econometric production models for each system being considered. The Century model computes changes in soil carbon (C) and crop yield by system as a function of climate change and CO_2 change. These crop yield changes are passed to the econometric process simulation model, where the expected economic value of each system is simulated and the system with the highest expected value is selected for a given land unit and time period. Based on the system choice, the economic model simulates management decisions, production and net returns for each land unit and time period in the analysis. The information on system choice by land unit is combined with the Century model's data on soil C by system to calculate the change in soil C per land area. Finally, the data on soil C and net returns by land unit are aggregated and used to construct the spatial distributions of soil C and net returns for the population.[1]

3.1. Application to Dryland Grain Production Systems in the U.S. Northern Plains

The integrated assessment approach described in the previous section was used to analyze the effects of climate change in the dryland grain production systems typical of the U.S. northern plains region. For this analysis we utilized data from the principal agricultural zones of Montana (roughly, the 100,000 square mile region east of the Rocky Mountains) where small grain production (wheat and barley) and pasture are the principal land uses. Some areas (such as the so-called Golden Triangle region of north-central Montana) are well-suited to the production of high-quality wheat and barley, whereas other areas are economically marginal for grain production due primarily to inadequate precipitation. Particularly in these marginal areas, relatively small reductions in precipitation could lead to substantial changes in production systems, primarily from grain production to pasture.

Several management strategies are used by farmers to deal with climate variability. A significant proportion of small grains are produced in a crop-fallow rotation, with the purpose of the fallow to accumulate soil moisture for subsequent crops. Many farmers follow the practice of fallowing a field every other year, but if soil moisture is adequate they may plant a crop in two or more subsequent years. Yet other farmers (presumably, in locations with greater precipitation) typically follow a continuous cropping strategy and rarely if ever leave a field fallow.

Another management strategy to deal with climate variation utilizes the different growing periods of winter wheat (planted in the fall) and spring wheat (planted in the spring). For example, a farmer may plant a winter wheat crop in the fall, and if the crop fails (because of adverse weather) a spring wheat crop may be planted in the same field. Farmers also may grow permanent grass for pasture, or convert agricultural land to conserving uses and obtain income from government conservation programs that pay farmers for planting grass or trees.

3.2. The Century Crop-Ecosystem Model

Century is a generalized biogeochemical ecosystem model that simulates carbon (i.e., biomass), nitrogen and other nutrient dynamics. The model has been used previously in several regional studies of climate change impacts on managed ecosystems (e.g., Ojima et al., 1993; Parton et al., 1995; Paustian et al., 1996, 1997). It includes submodels for soil biogeochemistry, growth and yield submodels for crop, grass, forest and savanna vegetation and simple water and heat balance functions. The model employs a monthly time step and the main input requirements include monthly precipitation and temperature, soil physical properties (e.g., texture, soil depth), atmospheric nitrogen inputs and management practices such as crop rotation, tillage, and fertilization.

Subdivisions of MRLAs (Major Land Resource Areas) were the primary spatial units used in the Century simulations (Figure 3). MRLAs are ecoregions defined by topographic and land use characteristics (SCS, 1981). In addition to comprising areas of similar topography and land use, MLRA’s are well-suited for broad scale analyses of agricultural systems because other databases such as soil maps are georeferenced by MLRAs. In delineating spatial units, we first eliminated areas under forest cover, by overlaying landcover from Loveland et al. (1991). MRLAs were then subdivided to further reduce the variability in climate (particularly precipitation) within each polygon, resulting in subunits having ‘high’ and ‘low’ precipitation totals.

Mean long-term climate variables for each polygon were calculated by overlaying the sub-MLRA coverage with the PRISM (Parameter-elevation Regressions on Independent Slopes Model; Daly et al., 1994) database, consisting of 4 km^2 polygons for the conterminous U.S. Climate variables in PRISM are based on 30-year mean (1960–1990) weather station records, spatially interpolated to account for topographic effects.

Soil physical properties for each polygon were derived from STATSGO soil association maps (SCS, 1994) overlaid with the sub-MRLA coverage. For each STATSGO map unit occurring within a sub-MLRA, we extracted the component (i.e., soil series level) attributes. Soils that represented at least 5% of the area within the MLRA were included in the analysis and grouped according to soil texture classes, such that 3–5 textural classes were usually represented within each region. Areas within each textural class for map units occurring within a sub-MLRA were used for computing area-weighted averages of simulation results.

To initialize the model, the model was run for 8,000 years to attain equilibrium values of soil C and N pools representative for native short-grass prairie, for each soil type within each spatial polygon (i.e., sub-MRLA). We then simulated two historical management scenarios for each soil-climate combination, involving either plow-out (in 1900) and cultivation under a wheat fallow rotation, or grazing on native rangeland. For the historical cropping sequence (1900–1975), data from long-term cropping experiments at Swift Current in southern Saskatchewan (Campbell and Zentner, 1997) were used to parameterize the crop model for regional conditions and historic crop yields were calibrated to match with state and county average yields compiled by the National Agricultural Statistics Service (NASS, 1999). To represent current conditions, the dominant management systems (spring cereal-fallow, continuous spring cereals, winter wheat-fallow, continuous winter wheat, cropland converted to perennial grasses and uncultivated rangeland) were run for 33 years (1975–1998) to represent present day (baseline) conditions.

3.3. The Econometric-Process Model

The econometric-process modeling approach was developed to simulate the farmer's choice of production system on a site-specific basis to assess economic and environmental impacts of changes in agricultural production systems (Antle and Capalbo, 2001). In this approach, a statistically representative sample of observations of farmers' fields are used to estimate econometric production models. These data and models are then incorporated into a simulation model that represents the decision-making process of farmers as a sequence of discrete land use and continuous input use decisions on a site-specific basis. This modeling approach provides the capability to simulate the changes in the spatial distribution of agricultural production systems and changes in economic attributes of those systems (e.g., net returns) in response to changing climate scenarios.

The econometric-process simulation model is constructed by estimating a system of equations representing output supply and input demand for each production activity, and then carrying out a stochastic simulation of these equations using site-specific data. For each field, expected returns are simulated and used to solve for the choice of production system on each land unit in each time period. In the present application, econometric models for winter wheat, spring wheat and barley crops were specified as a system of log-linear equations (a supply function, a machinery cost equation, and factor demands for variable fertilizer and pesticide inputs). The equation systems were estimated using non-linear three-stage least squares with zero-degree homogeneity of the supply function and linear homogeneity of the variable cost function imposed. To implement the econometric-process simulation model, a statistically representative sample of 850 fields from the Montana sub-MLRAs was used. The econometric models were simulated to estimate expected output and cost of production and calculate expected returns above short run variable costs of production for each crop and management alternative on each field in each time period. Based on the maximization of expected returns, a fall decision is made to produce winter wheat, to produce a spring crop, or fallow the field. If winter wheat is not grown, the model advances to the spring decision, where either spring wheat, barley, or fallow options are selected based on expected returns maximization. To appropriately couple the econometric-process model with the Century model, yields in the econometric model were assumed to change in proportion to the yields predicted by the Century model under alternative climate and CO_2 scenarios (Darwin and Kennedy, 2000). The econometric-process simulation model was calibrated to predict the observed mean frequencies of crops produced in the sample data. The model was calibrated using three parameters: the expected yield variability, the discount rate, and the expected future crop price. To validate the model, both within-sample and out-of-sample tests were performed (for details see Antle and Capalbo, 2001).

The econometric-process simulation model incorporates *endogenous adaptation* in the form of changes in both management decisions for a given system (as represented by input demand equations) and in the form of the choice among systems (as represented by the choice of system on each land unit). The discrete choice among production systems can be defined over any set of technological options that are available, including different crop cultivars, different types of crops, etc. The models can be formulated to represent dynamics within a growing season such as choice of planting date and timing of input decisions (as in Antle, Capalbo, and

Crissman, 1994), as well as dynamics across seasons such as crop rotations (as in Antle and Capalbo, 2001), and production risk (Antle and Capalbo, 2002).

Much of the economics literature on agricultural impacts of climate change is based on the use of representative-farm optimization models, based on either individual farm data (e.g., Kaiser et al., 1993) or aggregate data (e.g., Adams et al., 1999). Farm-level optimization models provide similar capabilities to represent adaptation through economic decision-making (choice of crops, inputs, etc.). The econometric-process modeling approach differs fundamentally from an optimization model (e.g., a linear or non-linear programming model) in the way that farmer decision making is represented and simulated. In a representative-farm optimization model, expected returns are compared for alternative activities as functions of prices, technology parameters and resource constraints. To apply the representative model to a region, the same economically optimal activity must be attributed to all land units. In an econometric-process model, simulated economic decisions are based on draws from the *spatial and temporal distributions* of expected returns that are representative of the population. Thus, as repeated draws are made from the underlying distributions, realistic spatial and temporal distributions of economic decisions are obtained that represent the population.

The econometric-process approach simulates land use and technology choice decisions at the level of the decision unit (the farmer's field) and thus is well-suited to study non-marginal changes in production and land use that may be associated with climate change. An important possibility is that some activities that are economically viable under the base climate may not be viable under a perturbed climate. Most econometric models are not well suited to analysis of climate change because they are based on estimation of continuous response variables (e.g., land-use share equations) that do not easily accommodate zero values for the dependent variables. The econometric-process model approach overcomes this problem by embedding a conventional econometric production model for each activity within a stochastic simulation model that represents discrete choices among alternative land uses.

A number of studies of agricultural impacts of climate change use sector models to study land use and associated environmental impacts, and these models are able to represent market equilibrium responses to policy scenarios (e.g., Adams et al., 1993, 1999; Darwin et al., 1995). These sector models use data aggregated to represent political or agro-ecological units, and thus cannot represent the spatial heterogeneity within an agro-ecological zone that is measured with the use of field-level data. However, an advantage of these large-scale models is that they can simulate the impacts of climate change on equilibrium prices. A limitation of the econometric-process approach (and other disaggregate models) is that they do not simulate market equilibria. With disaggregate models, alternative price equilibria can studied using sensitivity analysis, as we illustrate below. Alternatively, the disaggregate analysis can be linked to market models, but at the cost of greater complexity.

4. Analysis of Climate Change and CO_2 Fertilization Impacts

We analyzed impacts for different combinations of changes in climate and atmospheric CO_2 using the Canadian Climate Change (CCC) general circulation model (GCM), compiled in the Vegetation-Ecosystem Modeling and Analysis Project dataset (VEMAP, 1995). We note that a single climate change scenario is adequate to the hypotheses presented above. The VEMAP dataset spatially interpolates the results of the GCM model to 0.5x0.5 degree grid cells and there are only a few cells spanning the Montana study area. Thus, we used the average latitude and longitude of each sub-MLRA to determine the nearest grid cell in the VEMAP dataset. The simulated monthly changes in temperature (expressed as a difference) and precipitation (expressed as a ratio) of projected climate, relative to current climate from the VEMAP dataset, were applied to our base climate (i.e., PRISM-derived) for each sub-MLRA. Under the 2xCO_2 conditions, changes in MAP (mean annual precipitation) ranged between 2–5 cm across the sub-MLRAs and the increase in MAT (mean annual temperature) was between 4.5 and 4.8 degrees C. These estimates for changes in MAP and MAT are consistent with the range of estimates provided by the IPCC Third Assessment Report (IPCC, 2001) (for details, see Paustian et al., 1999). Carbon dioxide levels were set at current ambient (370 ppm) or 640 ppm.[2]

To generate input to the econometric model for climate and CO_2 change impacts on productivity and soil carbon, we simulated all possible management transitions for each of the six production systems. The climate scenarios were simulated by imposing a step change in climate and/or CO_2 and then simulating the model for a 50 year period and computing the percentage change in crop productivity and soil C (after 50 years), relative to the baseline.

The relative changes in productivity and soil carbon from Century were passed to the econometric simulation model, which then simulated the changes in management according to the economic outcomes that determine the farmer's decision making. Thus, adaptation in the form of changes in land use (choice of crop, crop rotation) and management (fertilizer, pesticides, machinery) is an endogenous property of the two models working together. We note that other adaptations, such as choice of planting date, could be incorporated into our analysis, as has been done in other studies that utilize crop response models with daily time steps (e.g., Kaiser et al, 1993; Easterling et al., 1993, 2001; Rosenzweig et al., 1994). However, the monthly time-step version of the Century model that we are using is designed to simulate the response of the crop ecosystem over long time periods, and is less sensitive to specific assumptions about planting date and timing of management decisions than daily time-step models. Therefore, we have chosen to focus our analysis on the economic adaptations brought about through choice of production system rather than on agronomic adaptations. To the extent that our analysis ignores relevant adaptations, our estimates of vulnerability to climate change may be overstated.

4.1. Climate Change and CO_2 Impacts on Yields

The yield changes predicted by Century (by crop, production system, and sub-MLRA) are summarized in Table 1 for alternative climate and CO_2 scenarios. Changes in climate without the effects of CO_2 fertilization resulted in a decline in grain yields for all systems and all sub-MLRAs, with yield levels ranging from 45% to 80% of baseline values. In contrast, grass yields increased by 10% to 20% above base values, mainly due to temperature increase. Yields of all crops increased under elevated carbon dioxide levels with winter and spring wheat showing positive responses of 17% to 55% across the sub-MLRAs. The crops grown after fallow often showed less of an increase than the same crop grown on land that was previously cropped. When the effects of climate and elevated CO_2 were combined, the changes in yields tended to be offsetting. The net result was an overall decline for spring wheat yields of 20% to 30%, and an increase in winter wheat yields and yields of grass grown for pasture. Looking at spatial variability in yields, winter wheat yields increase in nearly all sub-MLRAs, while spring wheat yields declined in all areas except 53A-high and 53A-low, which are the colder temperature areas.

4.2. Choice of Production System and Mean Net Returns

The econometric-process model computes net returns by production system to determine the choice of system. Table 2 present results for mean net returns by sub-MLRA and by climate change and CO_2 scenario. The allocation of land among systems for each sub-MLRA is shown in Table 3, by scenario. The base scenario replicates observed data showing that on average about one third of agricultural land is continuous crops and grass, with the remainder in crop-fallow systems. However, this allocation varies substantially by sub-MLRA, reflecting different resource endowments.

Table 2 shows that base-climate net returns vary substantially across the sub-MLRAs, ranging from over $100 per acre in sub-MLRAs 52-high and 52-low (known to be the most productive grain producing region in Montana), to $60–$70 per acre in the other sub-MLRAs (note, these net returns are revenue minus variable costs of production, and can be interpreted as returns to land and capital ownership, family labor, and risk). Net returns tend to follow the patterns of yield changes shown in Table 1, and reflect the relative advantage of each sub-MLRA in the different systems. The climate-change-only scenario shows a substantial negative impact on returns in all sub-MLRAs, with the largest absolute impact in the most productive areas where the highest proportion of land is in crops. The CO_2-only scenario shows, conversely, a highly positive impact on returns because of the higher yields, and the combined CC+CO_2 scenario shows that the negative impacts of changes in temperature and precipitation in the CC scenario are offset by the positive effects of CO_2 fertilization, with five of the eight areas showing a net positive impact under the CC+CO_2 scenario relative to the base climate scenario.

Compared to the no-adaptation scenarios, all scenarios show a smaller negative impact of CC with adaptation, and a larger positive impact of CO_2 fertilization, as expected. Table 2 shows that with the climate change (CC) scenario, the negative impacts on yields and returns to spring wheat and barley cause production system utilization to shift significantly towards winter wheat and grass. Thus, the results indicate that climate change in the northern Great Plains region would tend to shift utilization of production systems towards the pattern now typical of the central Great Plains, where winter wheat predominates grain production. The increases in temperature in the climate change only scenario also cause significant shifts from crops towards grass in lower-productivity regions, presumably because moisture increases are not adequate to sustain crop production at the higher temperatures in areas that are already marginal with respect to precipitation under the base climate.

4.3. Hypothesis 1: Net Returns Distributions, Endowments, and Adaptation

Figures 4 and 5 present the results of the simulations for the net returns distributions, by sub-MLRA, for each climate and adaptation scenario. These figures show that across climate and adaptation scenarios, there is a clear tendency for a negative relationship between mean returns and the second and third moments. Examination of the graphs shows that the scenario with the most adverse net returns distribution (the lowest mean, highest dispersion, most positive skew) is for the climate change scenario without adaptation, whereas the scenario with the most positive net returns distribution is CO_2 fertilization with adaptation.

The data in Table 3 show that sub-MLRAs 52-high and 52-low enjoy better endowments that give rise to higher productivity and higher mean economic returns. Figures 4 and 5 show that within each scenario, there is also a tendency for the set of points to exhibit a negative relationship between mean returns and the higher moments. However, with only eight sub-MLRAs, it is difficult to discern a clear pattern in all cases. A much clearer pattern emerges when we look across climate scenarios for a given adaptation scenario, or conversely across adaptation scenarios for a given climate scenario. Regressions of the coefficient of variation and skewness of net returns on mean net returns shows that there are consistently significant negative relationships between resource endowments (as proxied by mean net returns) and the higher moments of the net returns distribution. This finding supports the hypothesis that the most adverse impacts on net returns distributions tend to occur in the areas with the poorest resource endowments.

In Figures 4 and 5, solid markers indicate scenarios without adaptation and empty markers indicate scenarios with adaptation. Figure 4 shows clearly that across climate scenarios, adaptation is associated with higher mean returns and lower coefficients of variation. Figure 5 shows that the relationship between mean returns and skewness of the net returns is similar between the adaptation and non-adaptation scenarios. Thus, the overall effect of adaptation is to cause a more favorable net returns distribution.

4.4. Hypothesis 2: Vulnerability, Adaptation, and Endowments

We observed above that the climate change only scenario results in the most adverse impacts on the net returns distributions. In this section we use results from the climate change only scenario to evaluate the hypothesis that vulnerability is inversely related to adaptation and resource endowments. Figure 6 presents the mean values of the relative vulnerability measure RCVN (as defined in section 2) by sub-MLRA, plotted against mean net returns from the base scenario (a measure of resource endowment). To assess sensitivity to economic assumptions, the results are presented for three combinations of relative output prices: high grain prices and low grass prices; medium prices for each (corresponding to the baseline prices used in the results reported above); and low grain prices and high grass prices.[3] These changes in relative output prices change the relative profitability of the production systems being modeled, and thus change the vulnerability to climate shocks. To facilitate interpretation, note again that solid markers in the figures indicate scenarios without adaptation.

For relative climate vulnerability – no adaptation (RCVN), with medium wheat and grass prices, and with high wheat and low grass prices, there is no clear relationship between resource endowments and vulnerability. However, the case of low wheat prices and high grass prices shows a negative relationship between vulnerability and mean returns. This negative relationship reflects the greater utilization of the grass-based production system in the regions with poorer endowments. Without adaptation, these areas are much more vulnerable to reductions in grass yields when grass prices are high. The results for relative climate vulnerability with adaptation (RCVA) all show a positive relationship between vulnerability and resource endowments. In the case of low grain prices and high grass prices we see that the regions with poor resource endowments actually have negative vulnerability, that is, they gain from climate change, due to their ability to shift to grass-intensive systems. In contrast, with adaptation, the regions with better resource endowments (particularly, sub-MLRAs 52-high and 52-low) are vulnerable to climate change (with RCVA about 20%) because of their greater reliance on grain production.

For the analysis of vulnerability in relation to a threshold (Figures 7 and 8), we set the relative threshold at 30 percent and the absolute threshold at $50 per acre (these thresholds are arbitrary, and were chosen to be in the lower range of observed net returns). With adaptation, levels of vulnerability are low and there does not appear to be any systematic relationship to resource endowments across regions. However, without adaptation there is a tendency for a negative relationship between relative threshold vulnerability and endowments. As with Figure 6, this relationship is most pronounced in the case of low wheat prices and high grass prices. The absolute threshold measures of vulnerability (Figure 8) show a consistent negative relationship to resource endowments, thus confirming the prediction that systems in poorly endowed regions are closer to any absolute threshold than better-endowed regions, and therefore are at higher risk of falling below an absolute threshold when subjected to a climate change that has a generally adverse effect on productivity.

Comparison of Figures 6, 7 and 8 confirm the fact that with adaptation, measured vulnerability is generally lower than without adaptation. Indeed, the case of low grain prices and high grass prices shows that adaptation can greatly affect measured vulnerability. Without adaptation, relative vulnerability is measured in the 60 to 90 percent range, whereas with adaptation relative vulnerability is *negative*, indicating net gains from climate change. Likewise, the vulnerabilities measured with respect to a threshold change dramatically in this case.

4.5. Hypothesis 3: Endowments and Gains from Adaptation

The measures of relative adaptive gain (RAG) associated with the three output prices scenarios (Figure 9) confirm that the regions with poorer resource endowments tend to gain more from adaptation than the regions with better resource endowments. Likewise, examination of Figures 6, 7 and 8 shows a tendency for a larger reduction in vulnerability from adaptation for the less-well endowed regions.

5. Conclusions

In this paper we develop relative and absolute economic measures of vulnerability to climate change with and without adaptation, and we implement these measures using coupled, site-specific ecosystem and economic simulation models. This modeling approach has two key features needed to study the response of agricultural production systems to climate change: it represents adaptation as an endogenous economic response to climate change; and it provides the capability to represent the adaptive response of the population of spatially heterogeneous economic decision units. We apply this approach to the dryland grain production systems of the Northern Plains region of the United States to investigate the relationships between vulnerability, adaptation, and the spatial heterogeneity of agricultural production systems.

Our findings show that the spatial distributions of net returns vary systematically with assumptions about climate impacts, CO_2 fertilization, and adaptation. The results support the hypothesis that the most adverse changes in net returns distributions occur in the areas with the poorest resource endowments and when mitigating effects of CO_2 fertilization or adaptation are absent. We also find that the vulnerability of agriculture to climate change depends on how it is measured (in relative versus absolute terms, and with respect to a threshold), and it also depends on complex interactions between climate change, CO_2 level, adaptation, and economic conditions such as relative output prices. Moreover, we find that the degree of vulnerability of wealthier and poorer regions is highly sensitive to economic assumptions, such as changes in prices. Our results show that the relationship between relative vulnerability and resource endowments depends critically on the degree of adaptation, with a negative relationship emerging from the non-adaptation scenarios and a positive relationship from adaptation scenarious. However, vulnerability measured in relation to an absolute threshold appears to vary inversely with resource endowments across both adaptation and non-adaptation scenarios. Finally, we find that there is generally a positive relationship between gains from adaptation and the resource endowment of a region. This finding underlines the particularly important role that adaptation plays in mitigating climate change impacts in poorer regions.

These findings are the first to confirm with population-based survey data that the distribution of the economic impacts of climate change across regions with more and less favorable resource endowments is likely to depend on the ability of farmers in those regions to adapt to climate change. These findings are thus consistent with the conclusions of the IPCC Second and Third Assessment Reports (1996, 2001) that climate change is likely to have its greatest adverse impacts on areas where resource endowments are the poorest and the ability of farmers to respond and adapt is most limited.

As noted in the IPCC's Third Assessment Report (2001a), impact assessments need to be subjected to more thorough sensitivity analysis, and dynamic adaptive responses needed to be taken into account. Because of their relatively small size, the econometric process models used in this study can be subjected to sensitivity analysis using parametric methods and Monte Carlo methods. In addition, sensitivity analyses could be used to address the issue of how uncertainty in the parameters of process-based models (for which we lack statistical distributions) affects the results of an integrated assessment simulation. An example of this type of analysis can be found in Antle et al. (2002). An important limitation of this and most other integrated studies done to date is that they are limited to before-and-after, comparative static analysis of climate change. A topic of ongoing work is to dynamically couple the ecosystem and economic models to simulate adaptive responses to climate transients.

Notes

[1] Soil carbon is known to play an important role in crop productivity and thus should have an impact on vulnerability. Our use of the Century model (see section 3.2) allows changes in soil carbon to be taken into account in the estimated impacts of climate on crop yields.

[2] For the climate scenarios, the value of 640 ppm corresponds to the concentration of CO_2, which is projected for the atmosphere in which the total radiative forcing for all greenhouse gases will be twice that in the "present" baseline (355 ppm CO_2) climate scenario (Adams et al., 1990).

[3] Grass prices refer to the value of grass as pasture or as a conserving use of the land. High and low prices are 50% above or below the baseline. This is a range of price variation observed in market data over relatively short historical time periods, and one that induces substantial changes in net returns to different land uses.

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TABLE I
Yield Changes under the Climate Change and CO_2 Fertilization Scenarios, by Montana Sub-MLRA

	Grass	Winter Wheat Continuous	Winter Wheat Fallow	Spring Wheat Continuous	Spring Wheat Fallow
	------------------------ % of baseline ------------------------				
Sub-MLRA 52-high					
CC	118.5	71.7	72.3	49.9	52.7
CO_2	111.6	176.4	125.0	158.8	153.9
CC + CO_2	124.4	109.5	106.1	72.4	86.5
Sub-MLRA 52-low					
CC	107.4	65.4	74.4	54.1	54.8
CO_2	105.7	153.1	156.1	146.3	147.7
CC + CO_2	111.4	98.5	111.0	76.8	86.7
Sub-MLRA 53A-high					
CC	109.6	76.0	80.8	69.5	60.8
CO_2	107.9	155.5	139.7	159.4	155.7
CC + CO_2	113.3	118.2	124.1	101.9	101.0
Sub-MLRA 53A-low					
CC	106.3	73.8	80.8	69.6	66.1
CO_2	106.5	156.9	145.0	147.0	156.3
CC + CO_2	109.3	112.9	121.8	102.4	107.7
Sub-MLRA 54-high					
CC	116.2	65.4	79.0	50.3	45.2
CO_2	107.3	169.3	121.7	156.5	153.7
CC + CO_2	121.0	105.6	124.6	76.6	82.6
Sub-MLRA 54-low					
CC	115.3	65.3	73.5	60.7	55.4
CO_2	106.9	155.2	131.3	158.4	157.1
CC + CO_2	119.5	103.1	108.9	86.9	91.6
Sub-MLRA 58A-high					
CC	123.1	75.2	80.2	57.1	52.7
CO_2	109.9	171.9	119.0	161.0	155.8
CC + CO_2	129.9	113.0	121.5	93.7	91.9
Sub-MLRA 58A-low					
CC	119.6	62.5	73.3	59.4	56.0
CO_2	107.0	154.4	132.4	156.0	153.7
CC + CO_2	124.3	99.3	106.1	84.2	89.3

TABLE II

Mean Net Returns under Climate Change and CO_2 Fertilization Scenarios, by Montana Sub-MLRA

	Base	With Adaptation	Without Adaptation
	---------------- dollars ----------------		
Sub-MLRA 52-high			
CC	111.68	61.24	45.14
CO_2	111.68	184.44	157.56
CC + CO_2	111.68	102.19	81.29
Sub-MLRA 52-low			
CC	101.88	57.63	43.51
CO_2	101.88	163.62	139.72
CC + CO_2	101.88	93.61	75.08
Sub-MLRA 53A-high			
CC	61.73	43.17	29.98
CO_2	61.73	100.42	90.32
CC + CO_2	61.73	67.39	57.10
Sub-MLRA 53A-low			
CC	71.29	48.62	36.08
CO_2	71.29	120.33	101.64
CC + CO_2	71.29	82.09	67.75
Sub-MLRA 54-high			
CC	69.34	51.84	35.68
CO_2	69.34	110.52	97.41
CC + CO_2	69.34	81.78	69.83
Sub-MLRA 54-low			
CC	58.32	40.93	26.13
CO_2	58.32	90.69	79.80
CC + CO_2	58.32	59.81	50.09
Sub-MLRA 58A-high			
CC	66.24	48.85	30.33
CO_2	66.24	107.96	90.69
CC + CO_2	66.24	74.02	59.96
Sub-MLRA 58A-low			
CC	59.92	42.66	22.02
CO_2	59.92	96.19	83.41
CC + CO_2	59.92	57.38	43.16

TABLE III
Production System Utilization under Climate Change and CO_2 Fertilization Scenarios, by Montana Sub-MLRA

	Grass	Winter Wheat Fallow	Spring Wheat and Barley Continuous	Spring Wheat and Barley Fallow
	------------------------ share	-----------------------		
Sub-MLRA 52-high				
Base	0.01	0.12	0.44	0.43
CC	0.32	0.28	0.23	0.17
CO_2	0.01	0.06	0.64	0.30
CC + CO_2	0.05	0.29	0.42	0.24
Sub-MLRA 52-low				
Base	0.01	0.12	0.35	0.52
CC	0.28	0.25	0.19	0.28
CO_2	0.00	0.16	0.41	0.43
CC + CO_2	0.06	0.26	0.30	0.38
Sub-MLRA 53A-high				
Base	0.15	0.12	0.35	0.39
CC	0.60	0.13	0.15	0.12
CO_2	0.02	0.09	0.55	0.34
CC + CO_2	0.21	0.20	0.32	0.27
Sub-MLRA 53A-low				
Base	0.10	0.14	0.39	0.36
CC	0.40	0.18	0.24	0.17
CO_2	0.00	0.17	0.55	0.28
CC + CO_2	0.10	0.25	0.35	0.31
Sub-MLRA 54-high				
Base	0.16	0.49	0.17	0.19
CC	0.62	0.36	0.01	0.00
CO_2	0.00	0.36	0.51	0.13
CC + CO_2	0.30	0.61	0.08	0.01
Sub-MLRA 54-low				
Base	0.25	0.30	0.23	0.22
CC	0.68	0.25	0.03	0.04
CO_2	0.01	0.22	0.45	0.32
CC + CO_2	0.37	0.39	0.16	0.08
Sub-MLRA 58A-high				
Base	0.18	0.23	0.31	0.28
CC	0.63	0.30	0.04	0.02
CO_2	0.01	0.13	0.56	0.30

	Grass	Winter Wheat Fallow	Spring Wheat and Barley Continuous	Spring Wheat and Barley Fallow
CC + CO_2	0.26	0.41	0.17	0.16
Sub-MLRA 58A-low				
Base	0.18	0.12	0.34	0.36
CC	0.72	0.15	0.09	0.04
CO_2	0.02	0.07	0.51	0.40
CC + CO_2	0.40	0.20	0.23	0.16

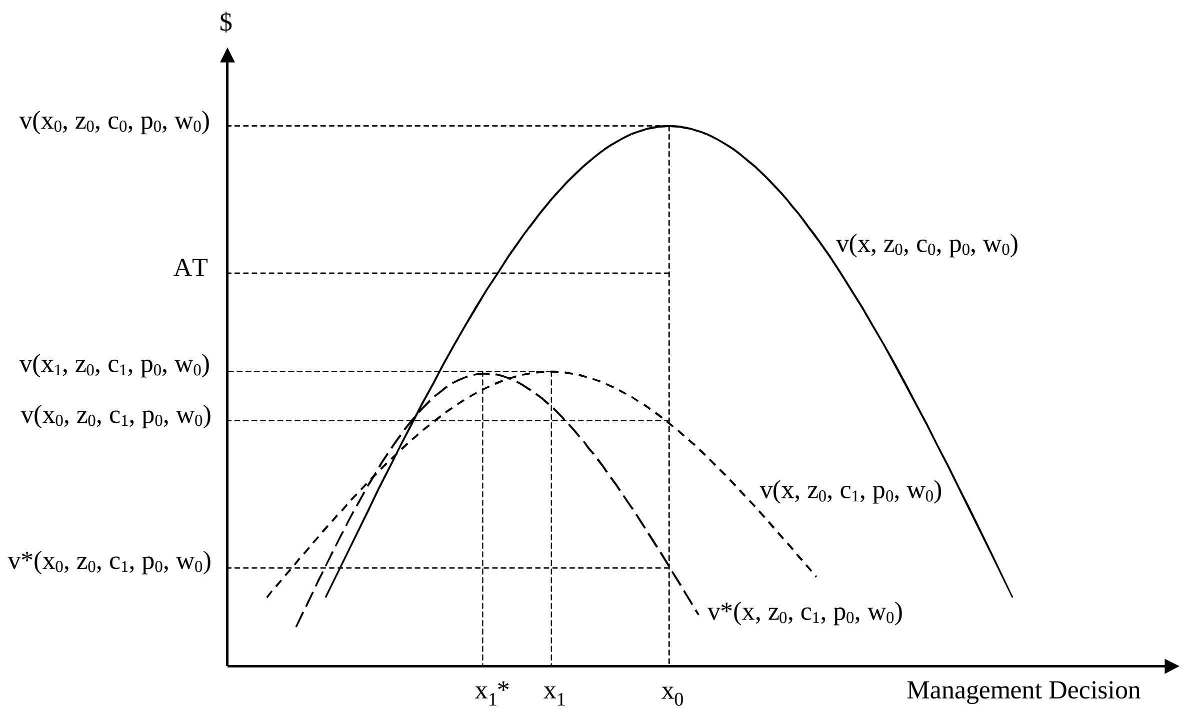

Figure 1. Economic analysis of adaptation to climate change.

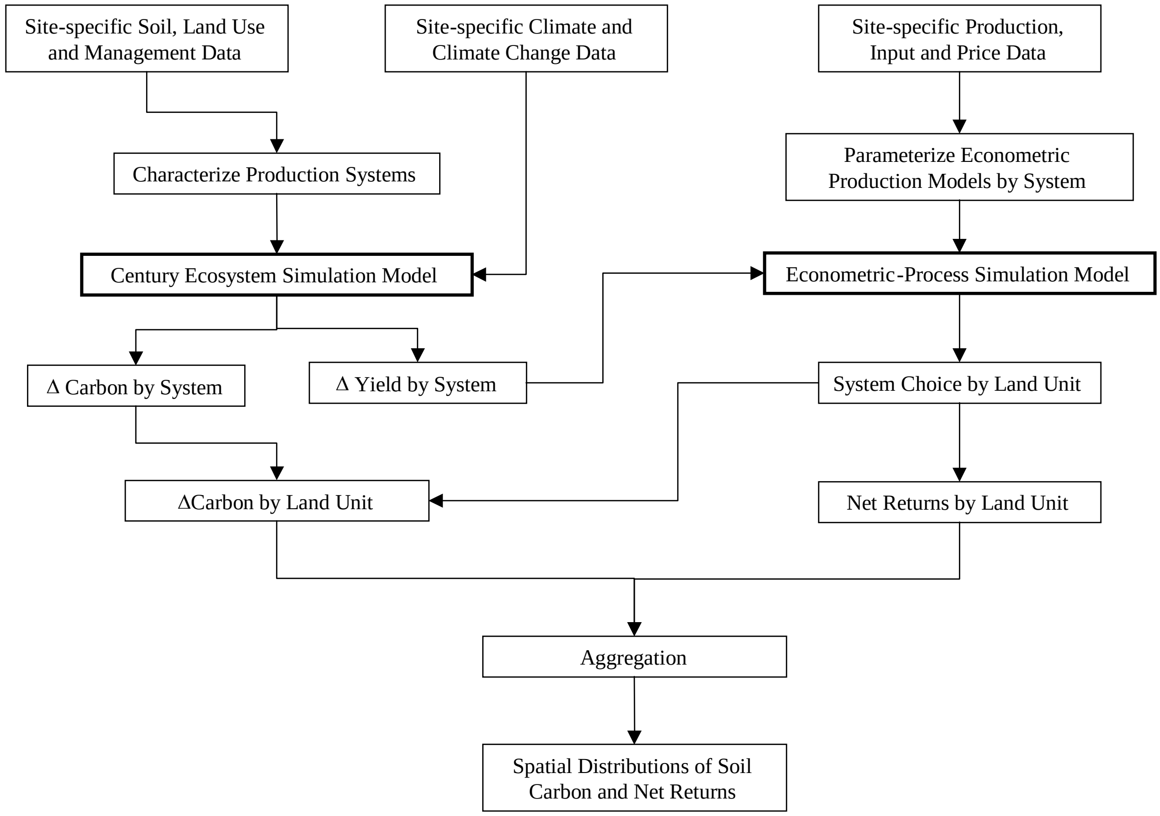

Figure 2. Integrated assessment of climate change impacts in an agricultural production system using coupled Century and econometric-process simulation models.

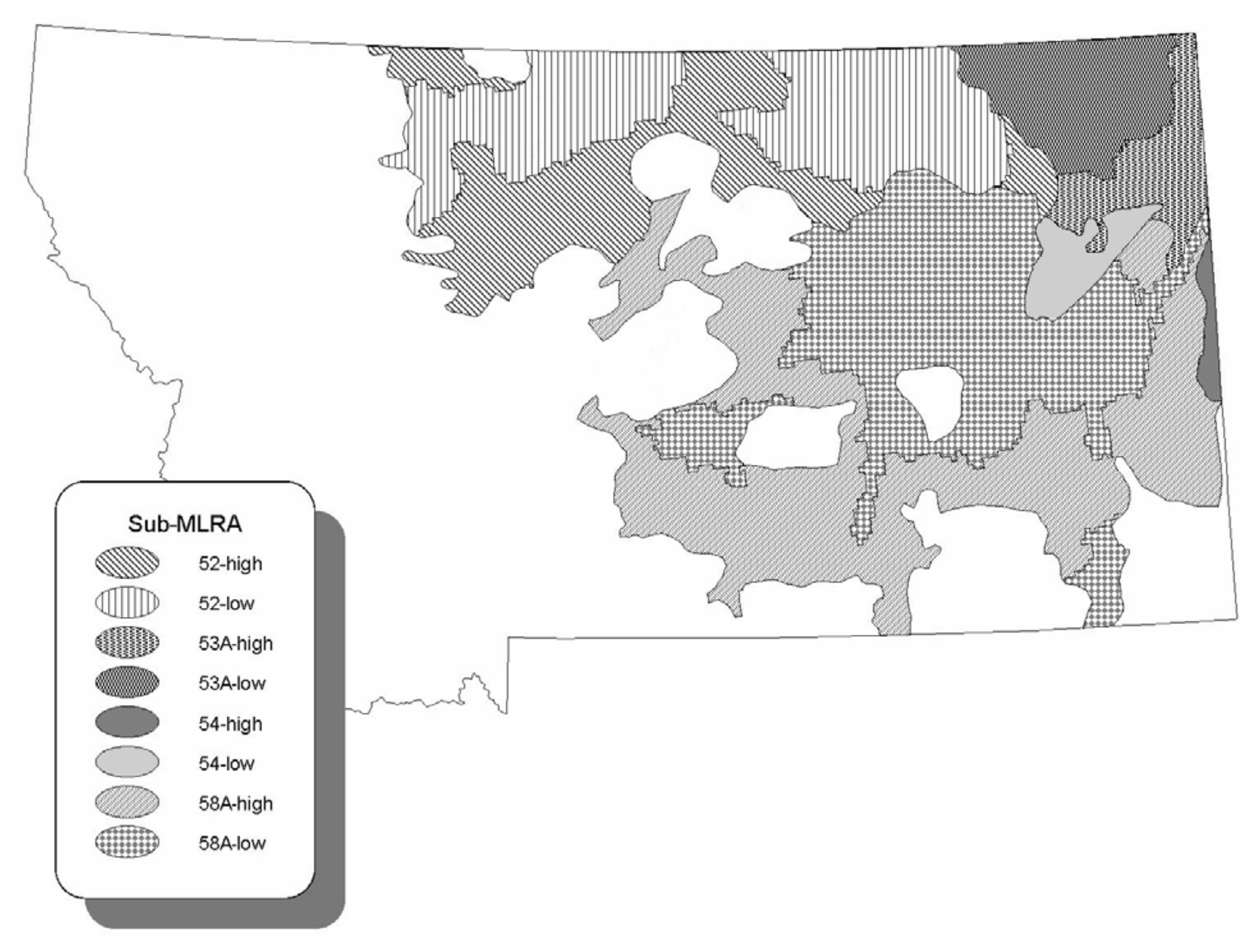

Figure 3. Major land resource areas in central and eastern Montana.

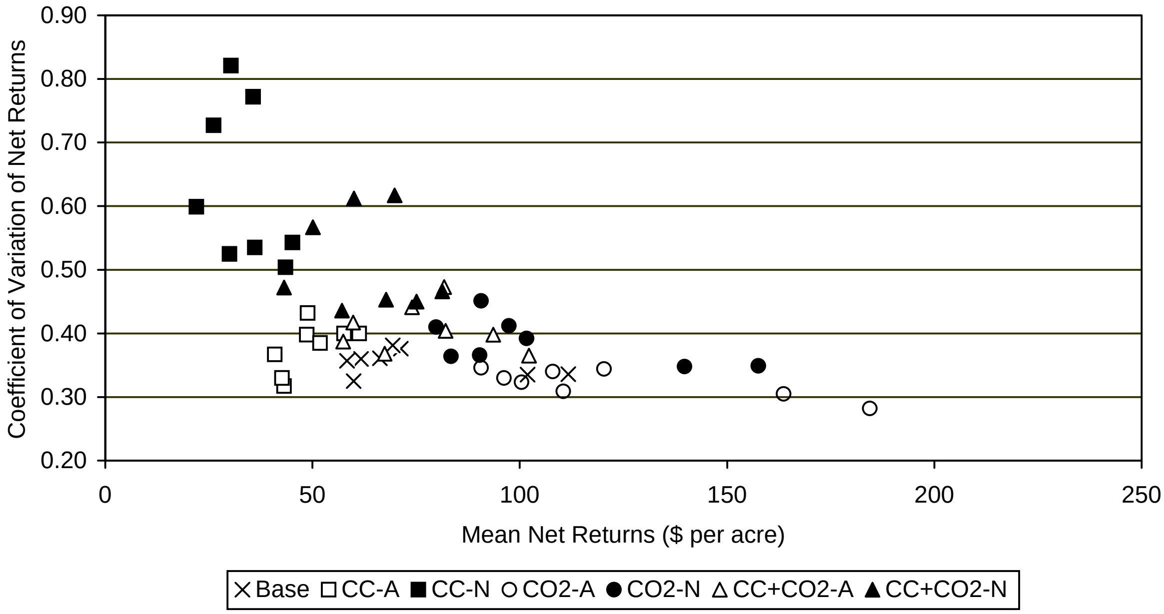

Figure 4. Mean versus coefficient of variation of net returns by Montana sub-MLRA, for climate change (CC) and CO_2 fertilization scenarios with (A) and without (N) adaptation.

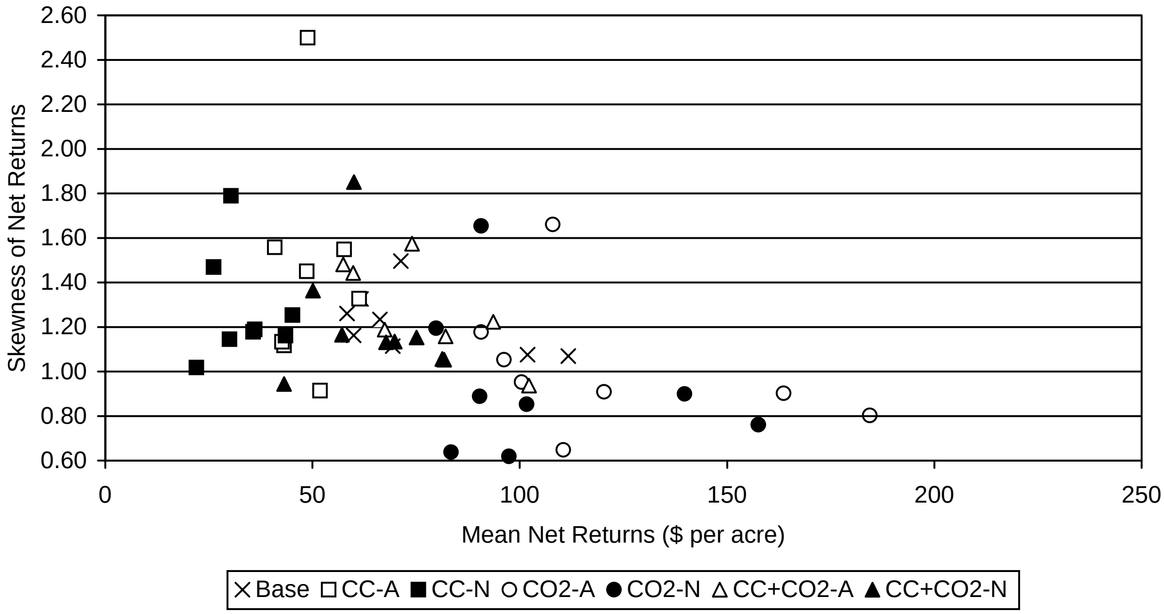

Figure 5. Mean versus skewness of net returns by Montana sub-MLRA, for climate change (CC) and CO_2 fertilization scenarios with (A) and without (N) adaptation.

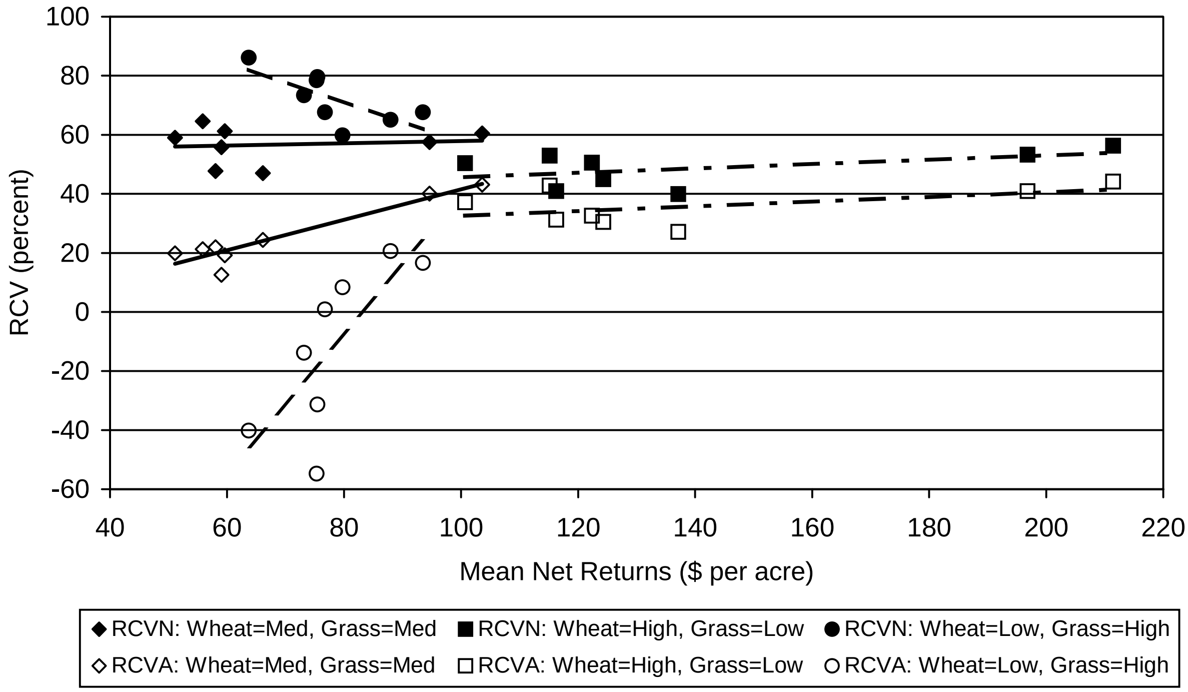

Figure 6. Relative climate vulnerability (RCV) by Montana sub-MLRA, with (A) and without (N) adaptation, for alternative wheat and grass price scenarios.

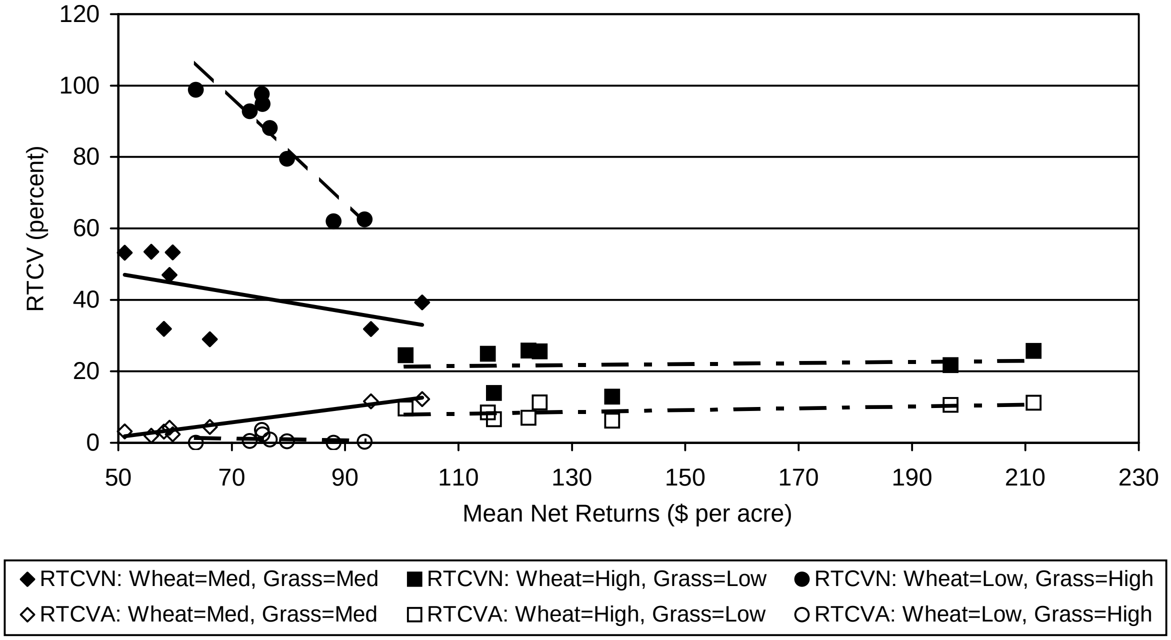

Figure 7. Relative threshold climate vulnerability (RTCV) by Montana sub-MLRA, with (A) and without (N) adaptation, for alternative wheat and grass price scenarios.

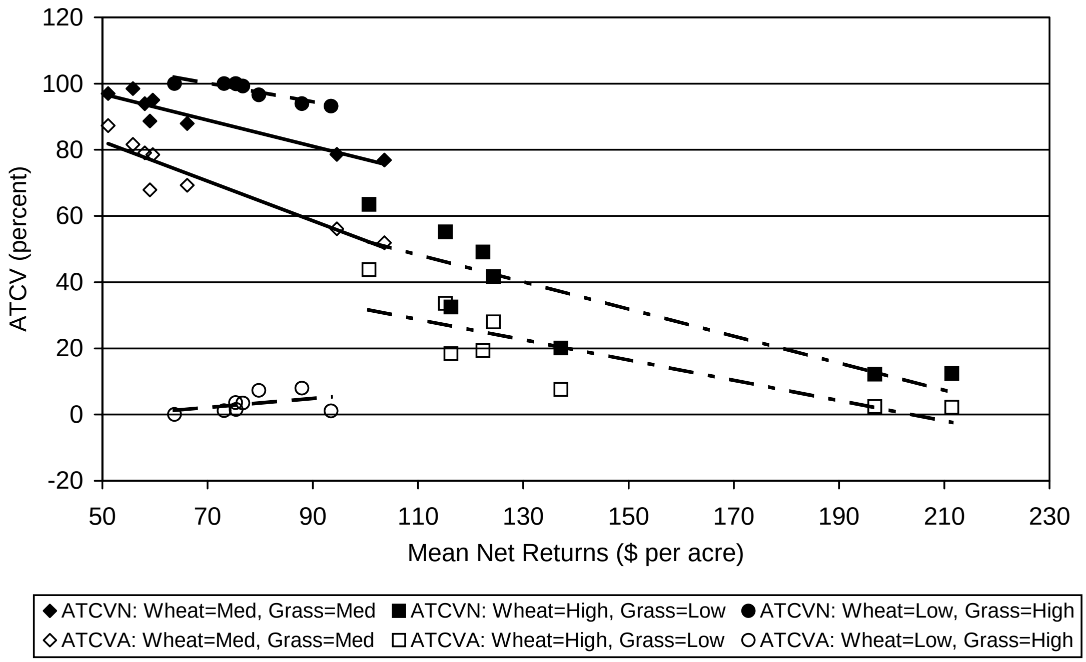

Figure 8. Absolute threshold climate vulnerability (ATCV) by Montana sub-MLRA, with (A) and without (N) adaptation, for alternative wheat and grass price scenarios.

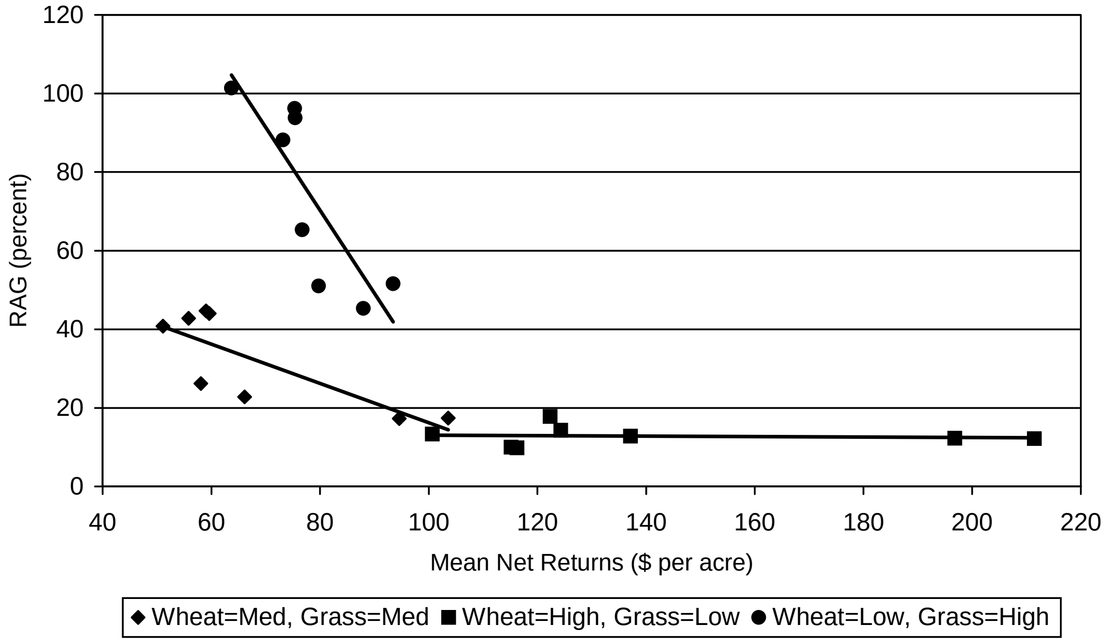

Figure 9. Relative climate vulnerability adaptive gain (RAG) by Montana sub-MLRA, for alternative wheat and grass price scenarios.