A FARMER'S VIEW OF THE RICARDIAN APPROACH TO MEASURING AGRICULTURAL EFFECTS OF CLIMATIC CHANGE

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Abstract. During the past few years two new methods, each based on the analogous region concept, have been developed to account for farmer adaptation in response to global climatic change. The first, called 'Ricardian' by Mendelsohn, Nordhaus, and Shaw (1994), econometrically estimates the impact of climatic and other variables on the value of farm real estate. Under some conditions, estimates of climate-induced changes in farm real estate capture first-round adaptations by farmers and represent the economic value of climatic change on agriculture. The second method, promulgated by Darwin et al. (1994) in the Future Agricultural Resources Model (FARM), uses a geographic information system to empirically link climatically derived land classes with other inputs and agricultural outputs in an economic model of the world. FARM provides estimates of economic impacts that fully account for all responses by economic agents under global climate change as well as estimates of Ricardian rents.

The primary objective of this analysis is to evaluate how well changes in Ricardian rents measure agricultural or other effects of climatic change after all economic agents around the world have responded. Results indicate that changes in Ricardian rents on agricultural land are poor *quantitative*, but good *qualitative*, measures of how global climatic change is likely to affect the welfare of agricultural landowners, *if one recognizes that increases in Ricardian rents actually indicate losses in landowner welfare and vice versa*. Results also indicate that regional changes in Ricardian rents on all land are good *qualitative* measures of changes in regional welfare. They are poor *quantitative* welfare measures because they systematically overestimate both benefits and losses and are on average upwardly biased because inflated benefits are larger than exaggerated losses. Results also indicate that, when based on existing land-use patterns, changes in Ricardian rents on all the world's land are poor *quantitative* and *qualitative* measures of changes in world welfare.

Despite these shortcomings, changes in Ricardian rents can provide useful information when other measures are not available. In this analysis, for example, estimated changes in Ricardian rents on all land indicate that climatic change would likely have detrimental effects in Latin America and Africa, beneficial effects in the former Soviet Union, and either detrimental or beneficial impacts in eastern and northern Europe and western and southern Asia. This is consistent with previous studies showing that climatic change would likely have detrimental, beneficial, and mixed effects on economic welfare in, respectively, equatorial, high latitude, and temperate areas. Estimated changes in Ricardian rents also indicate that aggregating Africa, Latin America, the former Soviet Union, eastern and northern Europe, and western and southern Asia into one region causes FARM's economic model to generate upwardly biased changes in world welfare. Modified results from scenarios with moderately flexible land-use change and which account for current land-use patterns indicate that world welfare may increase if the average surface land temperature does not increase by more than 1.0 or 2.0 °C. If the average surface land temperature increases by 3.0 °C or more, however, then world welfare may decline.

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1. Introduction

A major hurdle to estimating the effects of climatic change on agriculture has been how to incorporate farm-level adaptation into the analysis. In early studies a three-step approach was common. First, agronomic crop models simulate how climatic change might affect crop yields (Rosenzweig and Iglesias, 1994). Next, yields are further adjusted to simulate potential crop-specific farm-level adaptations. A major drawback in this step is that each adaptation (e.g., switching crop variety, changing planting or harvesting dates, etc.) has to be identified and assessed separately. Finally, yield changes are converted to supply changes in economic models that capture additional farm-level adaptations (e.g., switching crops, expanding or contracting acreage, etc.) to climate-induced price changes (Adams et al., 1988, 1990, 1995; Kaiser et al., 1993; Rosenzweig et al., 1993; Rosenzweig and Parry, 1994).

During the past few years two new methods have been developed to account for farmer adaptation in response to global climatic change. One, called 'Ricardian' by Mendelsohn, Nordhaus, and Shaw (1994), henceforth MNS, econometrically estimates the impact of climatic and other variables on the value of U.S. farm real estate at the county level.* Another, promulgated by Darwin et al. (1994, 1995, 1996) in the Future Agricultural Resources Model (FARM), uses a geographic information system (GIS) to empirically link climatically derived land classes with other inputs and agricultural outputs in a computable general equilibrium (CGE) economic model of the world. FARM's GIS can also estimate climate-induced changes in Ricardian rents.†

Both approaches rely on the analogous regions concept that similar climates mean similar production practices to implicitly capture changes in crop or livestock outputs, production inputs, or management practices that farmers are likely to adopt under new climatic conditions. Darwin et al.'s approach goes further, however, because FARM's CGE model simulates the additional interactions between farmers and downstream consumers (both domestic and foreign) of agricultural products that are likely to occur under climatic change. FARM, therefore, provides a consistent framework for investigating two questions concerning Ricardian rents as welfare measures once all economic agents around the world have responded. First, how accurately do changes in Ricardian rents measure changes in overall welfare caused by agricultural or other effects of climatic change? Second, to what extent do changes in Ricardian rents provide information about the effect of global climate change on specific agents, that is, who wins and who loses? The latter question is often of as much interest as the former.

* The approach was called 'Ricardian' because it relies upon standard theory of land rent, which originated with David Ricardo (1772–1823), as a way of identifying the impacts of changes on net economic welfare (Mendelsohn and Nordhaus, 1996).

† In Adams' (1999) terminology, FARM's GIS is a 'spatial analogue model' and FARM's CGE model is a 'structual model'.

The analysis is completed in three steps. First, I evaluate FARM's estimates of changes in Ricardian rents. Then I compare climate-induced changes in FARM's Ricardian rents with FARM-simulated changes in equilibrium income from agricultural land and overall economic welfare at regional and global levels. If changes in these measures are similar in size and direction to changes in Ricardian rents, one could infer that Ricardian rents are useful measures of agricultural or other effects of climatic change. Finally, I apply insights obtained from these comparisons in an analysis of climatic change in the Former Soviet Union, eastern and northern Europe, western and southern Asia, Latin America, and Africa – regions that are aggregated into one economic unit in FARM's CGE model.

1.1. THE RICARDIAN APPROACH

The Ricardian approach to estimating climate-induced impacts on agriculture was proposed by MNS (1994) as an alternative to crop simulation approaches. The underlying idea is that agricultural practices and land values are correlated with climate and that knowing their distribution across today's climatically variable landscape provides us with information about how farmers are likely to immediately respond to global climatic change and what such immediate responses mean for land values.

In a later work, MNS (1996) also showed that the value of climatic change is captured exactly by changes in land values if output prices and the prices of other inputs remain unchanged. Assuming constant output prices is appropriate when changes in the supply of crop and livestock commodities are not likely to affect their prices. Assuming constant input prices implies that all inputs are readily available at current prices and it, too, is appropriate when changes in the demand for inputs is not likely to affect prices.

Land values, in turn, can be thought of as the present values of infinite streams of annual net revenues or rents appropriately discounted. Hence, changes in agricultural land rents reflect exactly the annual value of climatic change to agriculture if output and other input prices remain constant. I call such rents Ricardian to distinguish them from rents that would occur if prices of outputs and other inputs were to change under global climatic change. Ricardian rents also embody the immediate adaptations that farmers are likely to take in response to climatic change.

The underlying functional form of the relationship between temperature and land values is expected to be hill shaped (see MNS, 1996). When temperatures are below 0 °C , for example, land is not suitable for agricultural production and Ricardian rents for such land approach zero. As temperatures increase above 0 °C, agricultural possibilities and Ricardian rents increase assuming that soil moisture conditions are suitable. Above some optimal temperature, however, agricultural productivity and Ricardian rents begin to decline.

1.2. MNS'S RICARDIAN MODELS

Two of MNS's most widely cited Ricardian models are from MNS (1994).* Both models are econometrically estimated using 1982 values of U.S. farm real estate at the county level as their dependent variable. Climatic influences are captured by linear and quadratic terms for temperature and precipitation in January, April, July, and October. Control variables are introduced to account for differences in soils, altitude, and proximity to markets. One MNS model used cropland and the other used crop revenues to weight observations during estimation. Cropland weights, e.g., the percentage of each county in cropland, tend to emphasize grain growing counties. Crop-revenue weights, e.g., the value of crop revenue in each county, emphasize counties where high value crops like fruits and vegetables are grown. For convenience, I refer to these models as the cropland model and crop-revenue model, respectively. Reported climate-induced changes in Ricardian land values from these models are sums over 2834 county level changes. Mendelsohn and Nordhaus (1996) used these models to estimate effects of climatic change on U.S. agriculture with results from various general circulation models (GCMs).

1.3. LIMITATIONS OF THE RICARDIAN APPROACH

As indicated above, for changes in Ricardian values to exactly capture the value of climatic change, output and input prices must remain constant. This is a strict constraint – one not likely to hold under global climatic change. First, farm-level adaptations made by farmers in response to global climatic change would likely generate supply changes that, in turn, would affect output prices. As supplies of these crops increase or decrease, their prices would decline or rise, respectively. Supply changes would likely be accompanied by changes in inputs and input prices as well. Second, global climatic change would likely affect agricultural resources in other countries, thereby affecting world prices and the demand for U.S. agricultural commodities (Kane et al., 1991; Rosenzweig and Parry, 1994; Darwin et al., 1994, 1995).

This in itself does not mean that changes in Ricardian rents have no value. If biases associated with price changes are relatively small and somewhat predictable, then changes in Ricardian rents may, perhaps with a little adjustment, approximate annual values of agriculturally related climatic change. Mendelsohn and Nordhaus (1996) indicate, for example, that welfare bias associated with a 25% climate-induced decrease in crop supply is likely to be less than 5% when demand is constant. They did not, however, evaluate the effects of increases in crop supply or changes in crop demand. If large enough, increases in crop supply can drive

* For more detailed descriptions of these and other Ricardian models see MNS (1994, 1996); Shaw et al. (1994); and Mendelsohn and Nordhaus (1996).

prices of agricultural products below their marginal costs of production causing farmers in some regions to cease production.*

This relates to another limitation of the Ricardian approach, specifically, changes in Ricardian rents do not provide information about the welfare implications of climatic change for specific agents. Schimmelpfennig et al. (1996), for example, pointed out that Ricardian models cannot assess how the effects of climatic change might be distributed among agricultural producers and consumers. Also, international trade can help transfer damages or benefits from one region to another. Such information is important to policy makers. To design workable international treaties, negotiators need to know not only the total magnitude of any economic benefits or damages that might be incurred under global climatic change, but also to whom such benefits or damages accrue, that is, who wins and who loses.

In summary, the value of Ricardian rents as welfare measures depends on the nature and size of the changes likely to occur under the climatic change scenarios being analyzed. To determine the magnitude of errors associated with such changes, however, one would like to compare climate-induced changes in Ricardian rents with changes in other economic measures that incorporate the full range of effects that would be generated by all major economic responses to global climatic change. Ideally, such a comparison also would shed some light on how well the Ricardian approach might indicate winners and losers under global climate change.

1.4. RICARDIAN RENTS IN FARM†

Like the MNS models, FARM simulates immediate farm-level adaptations to climatic changes while by-passing crop growth models (Darwin et al., 1994, 1995, 1996). Instead of direct econometric estimation, however, the FARM framework uses a GIS with over 62,000 half-degree grids to link climatic variables with agricultural production and land rents. FARM's GIS divides the world into twelve geographic regions – the United States, Canada, the European Community (as of 1990), Japan, other East Asia (South Korea and China, including Taiwan and Hong Kong), southeast Asia (Indonesia, Malaysia, Phillippines, Singapore, and Thailand), Australia and New Zealand, the former Soviet Union plus Mongolia, eastern and northern Europe plus Greenland, western and southern Asia, Latin America, and Africa.

* As an aside, it is not appropriate to cite small price changes from one study as evidence for unbiased Ricardian results in another study especially when estimated changes in Ricardian rents are large. Large changes in Ricardian rents imply large, not small, price changes.

† This section is longer than the preceding one simply because FARM's ability to evaluate changes in Ricardian rents is not presented elsewhere. For more details about FARM, see Darwin et al. (1995, 1996).

1.4.1. *Land Values in FARM*

Climate is captured by six land classes (LCs) defined by length of growing season – the longest continuous period in a year that soil temperature and moisture conditions support plant growth. Length of growing season forms the basis for the Food and Agriculture Organization's (FAO) agro-ecological zones (see FAO, 1996). Length of growing season is calculated in a soil moisture model (Eswaran et al., 1995) that requires mean values of temperature and precipitation for all months (Leemans and Cramer, 1991). LC 1 has a growing season of 100 days or less because of cold temperatures. LC 2 has a growing season of 100 days or less because of low precipitation. LCs 3, 4, and 5 have growing seasons of 101 to 165, 166 to 250, and 251 to 300 days, respectively. LC 6 has a growing season of 301 or more days.

Land-class boundaries generally reflect thresholds in crop production possibilities. Crop production in LC 1 and rain-fed LC 2 is marginal and restricted to areas where growing seasons approach 100 days. LC 1 and LC 2 (without irrigation) are limited to one crop per year. Principal crops on LC 3 are wheat, other short-season crops, and forage. LC 3, too, is limited to one crop per year. The growing season on LC 4 is long enough to produce maize as well as allow for some double cropping. Major crops on LC 5 are peanuts, tobacco, cotton and rice; double cropping is common. Year-round growing seasons characterize LC 6, which enables it to provide citrus fruits, sugar cane, and winter vegetables.

The GIS is also used to empirically link LCs with 1990 world production of crops and livestock. First, land-class distributions of cropland and pasture (FAO, 1992) are determined using land-use and cover data in Olson (1989–1991). Next, production of 33 crop and seven livestock aggregates are distributed, respectively, to cropland and pasture by LCs using regression analyses, crop distribution maps (U.S. Department of Agriculture. Foreign Agricultural Service, 1991), and livestock densities (Lerner, Matthews, and Fung, 1989). Then the 40 crop and livestock aggregates on each LC are summed, by region, to form four highly aggregated agricultural commodities – wheat, other grains, non-grains, and livestock. Total annual returns to cropland and permanent pasture (in 1990 dollars) for these four agricultural commodities, by region, are derived from cost data in the Global Trade Analysis Project (GTAP) database (Hertel, 1993) and distributed based on each LC's production share. A LC's total annual return to cropland is the sum of its annual returns to the three crop aggregates. Average rents for each land class are obtained by dividing total returns per LC by the number of hectares per LC.

Cropland rents generally increase as length of growing season increases. In the United States, for example, cropland rents are $30.25, $32.05, $44.89, $129.96, $123.78, and $196.31 per hectare per year for LC 1 through LC 6, respectively. Average rents for permanent pasture in the United States are $3.81, $16.71, $18.87, $41.25, $25.16, $20.85 per hectare per year for LC 1 through LC 6, respectively. It is highest on LC 4. Although these average land values were established indirectly, they conform fairly well to cash rental values in the U.S., which in 1990 ranged from $34.35 (Wyoming) to $259.46 (Florida) per hectare for non-irrigated cropland and $12.11 (Wyoming) to $87.23 (Indiana) per hectare of pasture (U.S. Department of Agriculture. Economic Research Service, 1992).

FARM also tracks forest and other land. Other land includes urban, suburban, and industrial land along with barren wilderness, wetlands, deserts, etc. Returns to forest land in FARM are approximately one third the returns to pasture. Rental values for urban, suburban, and industrial land in the current version of FARM are approximately equal to cropland rents. This assumption is based on the opportunity cost principle, e.g., that the cost of land used for urban and industrial purposes is the value that land would have had if it were used for other purposes, in this case, growing crops. Using cropland rents for opportunity costs isolates the biologically-based productive capacity of urban land from its productive capacity due to location near large capital aggregates.* Returns to barren land are assumed to be one-tenth the returns to forest land and are added to returns to land in the services sector. Cropland, pasture, and forest land is used intensively by crop, livestock, and forestry sectors, e.g., shares of production costs attributable to land in these sectors are high. Cost shares of land in other sectors is small.

1.4.2. *Calculating FARM's Ricardian Rents*

Once average land values are estimated, it is straightforward to calculate changes in Ricardian rents with FARM's GIS. Changes in Ricardian rents on agricultural land are derived by multiplying the climate-induced land-class distributions of existing cropland and permanent pasture by the appropriate rents. Cropland changing from LC 4 to LC 6, for example, is assigned LC 6's current cropland rent. This procedure maintains the Ricardian assumption of constant output and input prices. These methods are extended to all land uses to obtain changes in Ricardian rents on all land. The underlying assumption of Ricardian rent changes calculated this way is that land use is fixed in terms of FARM's broad use categories. Hence, these are referred to as 'land-use-fixed' (LUF) Ricardian rents. They generally conform to the changes in Ricardian rents presented in MNS (1994). FARM can also calculate changes in Ricardian rent based on the assumption that land-use shares in each LC are held constant. The latter, which are referred to as 'land-use-shares-fixed' (LUSF) Ricardian rents, reflect the possibility that climate affects what fractions of land are used for various purposes as well as the land's value, and may, therefore, generate better estimates of climatic change's economic value (MNS, 1996).

There are a few general limitations to these changes in Ricardian rents. First, FARM's method of aggregating climatic information into six LCs affects the sensitivity of Ricardian rents to changes in climatic variables at grid levels. As currently calculated, obtaining changes in Ricardian rents on FARM's individual 0.5°grids depends on how close the grids are to land-class thresholds. Relatively large climatic changes may be required to generate changes in Ricardian rents on grids that

* Returns to other land are lower in the version of FARM used in this analysis than in the version used in Darwin et al. (1995, 1996).

are not close to land-class thresholds. Similarly, relatively small climatic changes will generate Ricardian rent changes in grids that are close to land-class thresholds. These events tend to cancel each other, however, and, because the number of grids in each land-use/land-class category is large, should not result in any bias.

Second, FARM's changes in Ricardian rents do not explicitly capture some seasonal phenomena important to U.S. agriculture. These include (1) vernalization, a period of cold required by some plant species (e.g., winter wheat) before they will produce flowers and a harvestable crop; (2) precipitation's potential detrimental effects on field operations, particularly during planting and harvesting seasons; and (3) thermal regime, the effects that average air temperatures during growing seasons have on plant growth. Not including vernalization and muddy fields means that FARM's estimated changes in Ricardian rents are likely to be upwardly biased under global climate change where temperatures and precipitation are expected to generally increase. The magnitude of this bias is likely to be small. Not including thermal regimes means that FARM's estimated changes in Ricardian rents may be upwardly biased in tropical regions and downwardly biased in high latitude regions.

1.4.3. *Links with General Equilibrium Welfare Measures*

While FARM's GIS calculates changes in Ricardian rents, FARM's CGE model provides estimated changes in economic measures that take account of the responses of all economic agents. FARM's CGE model is an aggregation and extension of the GTAP model (Hertel, 1993, 1997). FARM's CGE model divides the world into eight geographic regions – the United States, Canada, the European Community (as of 1990), Japan, other East Asia (South Korea and China, including Taiwan and Hong Kong), southeast Asia (Indonesia, Malaysia, Philippines, Singapore, and Thailand), Australia and New Zealand, and the rest of world.

Each region has 11 economic sectors that produce 13 tradable commodities. The agricultural sectors are crops (which produce wheat, other grains, and non-grains) and livestock. Other traded commodities are (1) forest products, (2) coal, oil, and gas, (3) other minerals, (4) fish, meat, and milk, (5) other processed foods, (6) textiles, clothing, and footwear, (7) nonmetallic manufactures, (8) other manufactures, and (9) services. Each crops, livestock, and forestry sector in a region is divided in up to six subsectors – one for each LC. Land services required by commodity producers are rented from land supply agents, one for each LC in a region. Income obtained from land is spent on goods and services by households. FARM's CGE component is implemented and solved using GEMPACK (Harrison and Pearson, 1996).

One welfare measure tracked in FARM's CGE model is equilibrium income from agricultural land. Changes in equilibrium income from agricultural land indicate how climatic change affects the welfare of landowners – lower incomes mean that agricultural landowners have less money to spend on consumer goods and services. The term 'equilibrium' refers to conditions that exist once all economic agents have responded to climatic change. Income from land equals land rent times the amount of land rented. Percent changes in Ricardian rents on agricultural land are accurate measures of percent changes in equilibrium income from agricultural land if the immediate climate-induced changes in rent and the amount of agricultural land are not affected by additional response to climate change. Percent changes in Ricardian rents will differ from percent changes in equilibrium land income, however, if the total response to global climatic change either causes the actual rents to differ from the estimated Ricardian rents or affects the amount of land used for various agricultural purposes.

Another welfare measure calculated by FARM's CGE model is equivalent variation (EV), i.e., the difference, in terms of money expenditure at pre-climatic-change prices, between the level of consumer satisfaction under global climatic change and the level of consumer satisfaction under no climatic change. In this analysis, one can think of EV as a climate-induced change in equilibrium income from all land that, in turn, is normalized for changing prices of goods and services purchased by households. It is related to changes in Ricardian rents on all land because changes in income from all land also represent changes in expenditures, e.g., the amount of money that landowners as members of households have to buy goods and services. A change in Ricardian rents on all land, therefore, is a non-equilibrium change in money expenditure that is not adjusted for price changes.

2. Procedures

The procedures outlined in this section are designed to help answer two general questions: (1) are FARM's estimates of changes in Ricardian rents reasonable? and (2) how do changes in FARM's Ricardian rents compare with FARM-derived changes in other measures of economic activity after all economic agents (not just farmers) in all regions (not just the United States) have responded to climatic change? A positive answer to the first question is required for the comparisons to be valid. The comparisons then can be used to evaluate climate-induced changes in Ricardian rents as measures of economic welfare. Insights obtained from this evaluation can then be applied in other analyses of global climatic change.

2.1. REASONABLENESS OF FARM'S RICARDIAN RENTS

The main test for the reasonableness of FARM's estimated changes in Ricardian rents is to see if the relationship between climate and agricultural land values is consistent with a hill-shaped functional form. This is determined by regressing changes (and squared changes) in temperature (plus precipitation) ranging from $-5.0\,^{\circ}$C (and percent) to $+5.0\,^{\circ}$C (and percent) on changes in LUF Ricardian rents on agricultural land in each region. A significantly negative value on the squared climatic variable indicates a hill-shaped parabolic functional form.

For the U.S., FARM's estimated changes in LUF Ricardian rents are also compared with those derived from MNS's models and presented in Schimmelpfennig et al. (1996). These changes are estimated from climate change scenarios based on results from doubled carbon dioxide (CO_2) levels as simulated by the GCMs of the Goddard Institute for Space Studies (GISS), Geophysical Fluid Dynamics Laboratory (GFDL), United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU). Changes in average global temperature range from 2.8 °C to 5.2 °C; changes in average global temperature over land (except Antarctica) range from 3.0 °C to 6.0 °C (Table I).*

Various statistical tests are used in this comparison. Means are evaluated with two-way analysis of variance (ANOVA). Association is evaluated with contingency tables (sign patterns), Kendall's coefficient of rank correlation, and coefficients of product-moment correlation. Changes in Ricardian rents are evaluated in terms of percentages to minimize the effects of different base land values in 1982 and 1990. Ideally, changes in Ricardian rents derived from FARM and MNS's models would have similar means and be associated with one another. Finding similarities would tend to validate the models; dissimilarities would signal that Ricardian rents calculated by one or more models may not be reliable.

2.2. COMPARISONS WITH GENERAL EQUILIBRIUM WELFARE MEASURES

Comparisons of changes in Ricardian rents with general equilibrium welfare measures are divided into two sets. First, changes in Ricardian rents on agricultural land are compared with equilibrium income from agricultural land. These comparisons show whether or not the welfare effects implied by changes in Ricardian rents on agricultural land are specific to agricultural landowners. Then, changes in Ricardian rents on all land (also referred to as 'changes in Ricardian expenditure') are compared with EV (also referred to as 'changes in equilibrium expenditure'). These comparisons show whether or not the welfare effects implied by changes in Ricardian rents on all land are specific to regions or appropriate for the world as a whole. Means of regional measures are evaluated with paired-sample *t*-tests and two-way ANOVA. Means of global measures are evaluated with paired-sample *t*-tests. Association is evaluated with contingency tables (sign patterns) and/or coefficients of product-moment correlation.

Changes are evaluated in terms of percentages to minimize the effects of different values for land and expenditures in the regions. Percent changes in Ricardian rents on all land and EV for the world are sums of regional percent changes weighted by population. This approach also helps to avoid some of the problems associated with simply summing regional, dollar-delineated welfare measures. First, a simple sum of dollar values assumes income parity across regions. Income parity implies that the welfare generated by a dollar's expenditure in the U.S. is equal to the welfare generated by a dollar's expenditure in China despite the fact that a U.S.

* Results presented in this paper are based solely on changes in temperature and precipitation. They do not include enhanced fertilization effects associated with increasing concentrations of CO_2 in the atmosphere.

TABLE I

Summary statistics for the general circulation models used as the basis for climate change scenarios[a]

Model	Year calculated	Resolution (lat. ∗ long.)	CO_2 (ppm)	Change in average global		Change in average land	
				Temperature (°C)	Precipitation (%)	Temperature (°C)	Precipitation[b] (%)
OSU	1985	4.00° ∗ 5.0°	652	2.8	8	3.0	13
GFDL	1988	4.44° ∗ 7.5°	600	4.0	8	4.1	15
GISS	1982	7.83° ∗ 10.0°	630	4.2	11	4.3	14
UKMO	1986	5.00° ∗ 7.5°	640	5.2	15	6.0	8

[a] Climatic change scenarios generated by, respectively, the general circulation models of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).

[b] Includes all land except Antarctica. Sources of global information: for GISS, GFDL, and UKMO models, Rosenzweig et al. (1993). For the OSU model, Dr. Sanjay Dixit, Department of Meteorology, Pennsylvania State University, University Park, Pennsylvania, 16802 (pers. commun.).

dollar buys more goods and services in China than in the U.S. Second, a simple sum does not account for regional differences in population; an impact that affects 250 million people is given the same weight as an impact that affects 1,000 million people.

All changes in economic measures are derived from the GCM-based scenarios used to evaluate the reasonableness of FARM's estimated changes in Ricardian rents. Climatic change is simulated in FARM's CGE model by altering water supplies and the distribution of land across LCs within each region. In addition, FARM's land services supply functions are manipulated to reflect various assumptions regarding the immediate effects of climatic change on land use and the potential economic responses of producers. Three types of land-services supply changes are simulated. The first method fixes land use at its current distribution. In these circumstances, farmland owners and other agents are not allowed to alter their use of land; they may, however, change cropping patterns or the mix of other inputs such as labor, capital, and water. These are referred to as 'land-use-fixed' or LUF simulations.

The second and third methods allow the supply and demand for land services to adjust in response to the economic impacts of climate change. In the second method, however, the distribution of land across land uses in a given LC is not adjusted to account for the current pattern of land use. This implicitly imposes an immediate climate-induced redistribution of land use, which may arbitrarily increase or decrease initial endowments of agricultural land. These are referred to as the 'unadjusted land-use-shares' (ULUS) simulations. The third method explicitly accounts for the current land-use pattern. These are referred to as the 'adjusted land-use-shares' (ALUS) simulations.*

2.3. AN APPLICATION WITH FARM'S RICARDIAN RENTS

Insights obtained from the comparisons are applied in an analysis of global climatic change in the former Soviet Union (including Mongolia), eastern and northern Europe (Europe not part of the former Soviet Union or European Community), western and southern Asia (Asia except Mongolia, Japan, other East Asia, and southeast Asia, and Oceania except Australia and New Zealand), Latin America, and Africa. Welfare measures that account for all responses to global climatic change are not estimated for these regions individually because FARM's CGE model aggregates them into one Rest-of-World region. FARM's GIS, however, does track land use in these regions so we can estimate percent changes in Ri-

* ULUS is simulated by changing the quantities of land in each LC in each region, LC$i, j$, where i = 1–6 classes and j = 1–8 regions. LUF is simulated by changing LC$i, j$ and the quantities of each LC$i, j$ supplied to each sector, LS$i, j, k$, where i = 1–13 sectors, j = 1–6 classes, and k = 1–8 regions. ALUS is simulated by changing LC$i, j$ and structural parameters in the land services supply functions, $Ai, j, k = 100 * [\text{LS}i, j, k - \text{LS}i, j, k(\text{exp})]) \div \text{LS}i, j, k(\text{exp})$, where $\text{LS}i, j, k(\text{exp}) = \text{LS}i, j, k(\text{base}) * (100 + \%\Delta\text{LC}i, j) \div 100$ are the sectorial supplies of land services that would be expected if land-use shares were fixed.

cardian rents in these subregions with average land values for the Rest-of-World region as a whole. These estimates are reasonable so long as the rank orders of land values across land classes and uses in each subregion are similar to the rank order of land values in the Rest-of-World as a whole.

Two Ricardian measures are considered – percent changes in Ricardian rents on agricultural land and percent changes in Ricardian expenditure. The latter are derived by multiplying percent changes in Ricardian rents on all land by the share of income derived from land in each subregion. Regional shares of total income derived from land in FARM are: U.S., 0.0056; Canada, 0.0075; European Community (in 1990), 0.0074; Japan, 0.0087; other East Asia, 0.0304; southeast Asia, 0.0387; Australia/New Zealand, 0.0115, and Rest-of-World, 0.0262. I set the shares of income from land in the former Soviet Union and other Europe equal to 0.020 and the shares of income from land in other Asia, Latin America, and Africa equal to 0.038. The assumption is that the Former Soviet Union and other Europe are somewhere between Australia/New Zealand and other East Asia, while other Asia, Latin America, and Africa are similar to other East Asia. These shares are also consistent with land income for the Rest-of-World region as a whole.

3. Results

The first set of results in this section pertains to the quality of FARM's estimated changes in Ricardian rents. Then I present and compare FARM's Ricardian measures with FARM's general equilibrium welfare measures. Finally, Ricardian measures for FARM's Rest-of-World region are presented and evaluated.

3.1. REASONABLENESS OF FARM'S RICARDIAN RENTS

This section presents the relationship between FARM's Ricardian rents and temperature (plus precipitation) in all regions and a comparison of FARM's estimated changes in U.S. Ricardian rents with MNS results.

3.1.1. *Climate and Agricultural Land Values*

Regional results of regressing changes in temperature (plus precipitation) on changes in LUF Ricardian rents on agricultural land are presented in Table II. Parameter estimates on the squared climatic variable are significantly negative in five regions – the United States, European Community, other East Asia, Australia/New Zealand, and Rest-of-World region. Parameter estimates on the squared climatic variable in the remaining regions are negative in Canada and southeast Asia, but positive in Japan. These parameter estimates, however, are not statistically different from zero, thereby denoting a linear relationship between climate and Ricardian rents over the range of temperatures (plus precipitation) analyzed.

These results are not very surprising. The relationship between temperature and Ricardian rents is expected to be hill shaped near some optimum. The relationship

TABLE II

Effects of temperature and precipitation on Ricardian rents from existing agricultural land in all FARM's CGE regions as simulated by FARM[a]

Variable	Region							
	United States	Canada	EC	Japan	OEA[b]	SEA[c]	ANZ[d]	Rest of world
Climate[e]	Percent change							
–5	–11.36	–39.04	–35.91	–31.03	–14.18	12.33	–0.04	–3.10
–2	–1.25	–22.11	–7.48	–12.59	–6.55	5.61	2.65	–0.98
–1	–0.15	–10.86	–1.46	–8.80	–4.21	3.25	2.43	–0.43
1	0.59	10.70	–6.26	10.05	0.77	–5.80	–2.49	–0.07
2	0.07	18.72	–12.48	16.76	0.03	–13.23	–3.29	–0.07
5	–7.22	27.86	–22.05	38.54	–4.10	–24.38	–9.02	–0.60
Regression output	Beta coefficients and (*t* statistics)[f]							
Intercept	0.616	–0.245	–3.298	0.791	–1.312	–3.747	0.226	–0.169
	(2.995)	(–0.095)	(–1.388)	(0.854)	(–1.769)	(–1.489)	(0.355)	(–2.925)
Climate	0.401	7.295	0.908	7.090	1.142	–3.464	–1.028	0.245
	(7.378)	(10.703)	(1.445)	(28.962)	(5.823)	(–5.205)	(–6.124)	(16.042)
Climate squared	–0.394	–0.217	–1.043	0.123	–0.318	–0.120	–0.189	–0.068
	(–25.934)	(–1.40)	(–5.941)	(1.803)	(–5.798)	(–0.647)	(–4.031)	(–15.926)
R squared	0.995	0.967	0.903	0.995	0.944	0.873	0.931	0.992
Degrees of freedom	4	4	4	4	4	4	4	4

[a] Agricultural land refers to cropland and pasture land. Changes in Ricardian rents are derived by assuming that the amount and location of agricultural land in 1990 remain constant.
[b] Other East Asia (China, including Taiwan; Hong Kong; and South Korea).
[c] Southeast Asia (Thailand, Indonesia, Philippines, Malaysia, and Singapore).
[d] Australia and New Zealand.
[e] Change in temperature (°C) and precipitation (%). Temperature and precipitation changes are applied uniformly over the entire world.
[f] Critical values for *t* statistics with four degrees of freedom are 2.776, 4.604, and 8.610 for probability levels 5.0, 1.0, and 0.1%, respectively.

could be linear over a range of temperatures away from the optimum and still be consistent with an overall hill-shaped parabolic functional form. At a minimum, these regression results indicate that estimates of changes in Ricardian rents on agricultural in all FARM's regions are consistent with basic Ricardian principles.

3.1.2. *Comparisons with MNS's Changes in U.S. Ricardian Rents*

Effects of four climatic change scenarios on LUF Ricardian rents in the U.S. are presented in Table III. Three things are apparent at a glance. First, mean results

TABLE III

Effects of climatic change on Ricardian rents derived from various models

Scenario[a]	Mendelsohn et al. models, by weight[b]		Darin et al. model (FARM)[c]	Mean value[d]
	Cropland	Crop revenue		
		Percent change		
OSU	–90.4	–18.6	–10.0	–39.7 ± 109.7
GFDL	–114.5	106.7	–16.1	–8.0 ± 255.5
GISS	–29.6	52.7	4.1	9.1 ± 83.9
UKMO	–117.7	28.6	–4.4	–31.2 ± 190.6
Mean value[d]	–88.1 ± 78.0	42.4 ± 82.9	–6.6 ± 13.7	

[a] Scenarios based on results from doubled atmospheric carbon dioxide levels as simulated by the general circulation models of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).
[b] Change in annualized value of U.S. farm real estate. Derived from information in Table 3.3 in Schimmelpfennig et al. (1996), p. 18. Base value is $31.1 billion.
[c] Changes are for land-use-fixed Ricardian rents derived by assuming that the amount and location of agricultural land in 1990 remain constant. From Table 3.4 in Schimmelpfennig et al. (1996), p. 19. Base value is $24.3 billion.
[d] With 95% confidence limits.

appear to differ by model and scenario. Second, FARM and cropland model results are primarily negative, while crop-revenue model results are primarily positive. Third, results from MNS’s models span broader ranges than results from FARM.

3.1.2.1. *Comparing means.* Results from a two-way ANOVA indicate that, while there are statistically significant differences between mean results by model ($F_{2,6} = 11.64^{**}$), there are no statistically significant differences between mean results by scenario ($F_{3,6} = 0.99$).* Individual comparisons indicate that there are statistically significant differences between the cropland model mean and FARM mean ($F_{1,6} = 8.90^{*}$), but not between the crop-revenue model mean and FARM mean ($F_{1,6} = 3.31$). In order for this test to be valid, however, the different sets must be normally distributed and their variances must be equal. Distributions were tested for normality with the Kolmogorov-Smirnov one-sample test. The hypothesis that the distributions are normal could not be rejected at the 5% significance level. Homogeneity of the three sets of variances combined was tested with Bartlett’s test. This hypothesis, too, could not be rejected at the 5% significance level, but just barely; calculated $\chi^2_2 = 5.97$, while $\chi^2_{2,\mathrm{crit}} = 5.99$. Results from Bartlett’s test comparing the variance of FARM’s results with the variance of results from either

* I use *, **, and *** to indicate statistical significance at the 5.0, 1.0, and 0.1% levels, respectively. For additional information about the statistics, please contact me.

the cropland or crop revenue model separately indicates that in both instances the hypothesis of homogeneous variances should be rejected (e.g., $\chi_1^2 = 4.68^*$ and $\chi_1^2 = 5.84^*$, respectively).

These statistics indicate that cropland model results are significantly lower than results from either the crop-revenue model or FARM. And, although crop-revenue model results appear to be greater than FARM results, their means are not significantly different. Given the small sample sizes and the unequal variances, however, the possibility of a type II error in this case should seriously be considered. More importantly, mean results by scenario are not significantly different. This indicates that the underlying relationships between climatic variables and Ricardian values are not consistent across models.

3.1.2.2. *Comparing signs and scenario ranks.* Signs are important because they provide information about the underlying relationship between temperature (plus precipitation) and Ricardian rents embodied in the various models. FARM's generally negative results, for example, are in keeping with the parabolic relationship between relatively high increases in temperature (plus precipitation) and Ricardian rents depicted in Table II. Scenario results may differ somewhat from those in Table II, however, because scenario-based changes in temperature and precipitation are not equally distributed over the U.S. Negative results from MNS's models would indicate that their underlying functional forms between temperature (plus precipitation) may be similar to FARM's.

A 2×2 contingency table provides a simple test for the number of positive or negative signs. Calculated χ_1^2 statistics (with Yate's correction because expected frequencies are less than five) comparing the number of FARM's negative and positive values with the number of negative and positive values generated by the cropland and crop revenue models are 0.00 and 0.50, respectively. A χ_1^2 of 0.00 indicates that there is no statistical difference (at the 1% level) between FARM and cropland model results with respect to signs. A χ_1^2 of 0.50 indicates that FARM and crop-revenue model results may or may not be different with respect to signs – neither case is statistically significant at the 5% level.

Correlation coefficients are used to determine how rank orderings of scenarios differ from one model to another. Kendall's coefficient of rank correlation, τ, is 0.33 for FARM and cropland model results; it is 0.00 for FARM and crop revenue model results. A more general measure is the coefficient of product-moment correlation, r. Calculated r_2 of FARM results with cropland and crop revenue model results are 0.779 and –0.241, respectively. None of these coefficients indicates statistical association at the 5% significance level. Higher and positive values, however, do imply greater direct correlation, indicating that FARM results are more similar to cropland model results in terms of rank order.

3.1.2.3. *Comparing ranges.* The differences in variability indicated by Bartlett's test are seen in the ranges of model results. FARM's estimated changes in Ricardian rents, for example, range from –16.1 to 4.1%. MNS models produce estimates ranging from –117.7 to –29.6% and from –18.6 to 106.7% for the cropland and crop-revenue models, respectively. The differences are due to two factors. First, the size of potential changes in Ricardian rents is limited in FARM. As currently calculated, the range of FARM's possible Ricardian rents stretches from $6.7 billion to $47.2 billion (from –72.7 to 92.7% of the current value).* Although these limits might cause an error under very large changes in temperature, potential errors in this research are likely to be small. Second, there are no upper or lower limits to changes in Ricardian values in MNS's models. In the cropland model, for example, uniform temperature increases of 5 °C cause farm real estate values to fall by 101% (Table IV). In the crop revenue model, uniform precipitation increases of 5 cm (approximately 7%) cause farm real estate values to increase by 102%. Results in Table IV also indicate that the relationship between temperature and farm real estate values is hill-shaped in the cropland model, but U-shaped in the crop-revenue model, while the relationship between precipitation and farm real estate values is U-shaped in both models.

3.1.3. *Discussion*

These tests and comparisons indicate that FARM's estimates of Ricardian rents are reasonable in the U.S. and other regions. First and foremost, regional relationships between temperature and land values are consistent with a hill-shaped functional form. This satisfies a basic tenet of the Ricardian approach (MNS, 1996). Results in Table II also indicate how each region's average surface temperature over existing agricultural land compares with its agricultural optimum. Average temperatures over agricultural land in the European Community and rest-of-world regions are within 1.0 °C of their optimums. Temperatures over agricultural land in the United States and other east Asia are less than but within 5.0 °C of their optimums, while temperatures over agricultural land in Canada and Japan are less than their optimums by at least 5.0 °C. The average temperature over agricultural land in the Australia–New Zealand region is more than but within 5.0 °C of its optimum, while the average temperature over agricultural land in southeast Asia is more than its optimum by at least 5.0 °C.

Second, FARM's estimated changes in Ricardian rents are not similar to estimated changes in Ricardian rents provided by the particular MNS models evaluated in this analysis.† The dissimilarities reflect well on FARM's estimates because the MNS models have major deficiencies. The functional form of the relationship between temperature and land values in the MNS crop-revenue model, for example, is

* The former would occur if, under some cooling scenario, all cropland and pasture became LC 1. The latter would occur if, under some warming scenario, all cropland became LC 6 and all pasture became LC 4.

† Although based in part on material contributed to Schimmelpfennig et al. (1996), conclusions reached in this analysis differ from those contained in that publication.

TABLE IV

Farmland values and changes in temperature and precipitation: Estimated effects from Ricardian models in Mendelsohn et al. (1994)[a]

Weight/month	Change in temperature (°C)						Changes in precipitation (cm)					
	–5	–2	–1	1	2	5	–10	–5	–2	2	5	10
Cropland	1982 dollars											
January	689	302	155	–164	–336	–906	–292	–157	–65	69	178	377
April	–235	1	17	–48	–128	–559	–665	–269	–92	72	141	154
July	1156	520	269	–289	–596	–1634	942	269	59	5	134	670
October	–1192	–605	–324	367	777	2264	233	108	41	–38	–90	–163
Total	418	217	117	–134	–284	–835	218	–48	–57	107	362	1038
Crop revenue												
January	1223	541	279	–297	–611	–1657	–1270	–593	–227	214	509	935
April	–664	–136	–46	3	–38	–419	–1289	–404	–104	27	–78	–637
July	765	312	157	–159	–320	–814	1340	449	127	–56	–7	427
October	–949	–620	–350	431	942	2957	3139	907	204	8	419	2162
Total	375	97	40	–22	–26	67	1921	359	–1	193	843	2888

[a] Estimated from parameters for 1982 listed in Table III, p. 760, Mendelsohn et al. (1994). In Mendelsohn et al. (1994) temperature and precipitation are measured, respectively, in degrees Fahrenheit and inches; here they are measured in degrees Celsius and centimeters. Average annual temperature and precipitation in the 48 contiguous U.S. states are approximately 11 °C and 70 cm (calculated from Leemans and Cramer, 1991. The value of farm real estate in the 48 contiguous U.S. states in 1982 was 823 dollars per acre (from Jones and Canning, 1993, Table 1, p. 3).

U shaped rather than hill shaped.* The MNS cropland model, on the other hand, is biased toward agriculture in cooler climates – grain production in the U.S. corn and wheat belts (MNS, 1994). Its results are significantly lower than those estimated by FARM.

Finally, I want to emphasize that 'reasonable' does not mean 'perfect'. There is room for improvement in future versions of FARM as the discussion in Section 1.4.2 of this paper indicates. Nevertheless, FARM's minor shortcomings do not invalidate the next component of the analysis – a comparison of FARM's estimated changes in Ricardian rents with changes in other economic variables.

3.2. RICARDIAN RENTS AS WELFARE MEASURES

In this section, changes in Ricardian rents on agricultural land and on all land are compared with changes in equilibrium income from agricultural land and EV, respectively.

3.2.1. *Income from Agricultural Land*

Impacts of four climatic change scenarios on Ricardian rents from agricultural land are presented in Table V. LUF Ricardian rents indicate how climatic change might affect the value of existing agricultural land. LUSF Ricardian rents indicate how climatic change might affect the value of all agricultural land that climatic change might generate if the share of agricultural land within a given land class were solely a function of climate. Regionally, LUSF Ricardian rents are generally more positive or less negative than the LUF Ricardian rents.

LUF Ricardian rents generally increase in Canada, Japan, and other east Asia, and generally decrease in the U.S., European Community, southeast Asia, and Rest-of-World. Impacts in Australia/New Zealand are mixed. These results are consistent with the regions' locations with respect to their agriculturally optimum temperatures (Table II). Minor inconsistencies in Australia/New Zealand are attributable to relatively large increases in precipitation (approximately 15–40%). LUSF Ricardian rents generally increase in Canada, Japan, other east Asia, and Rest-of-World, and generally decrease in the European Community and southeast Asia. Impacts in the U.S. and Australia/New Zealand are mixed. Increases and decreases in LUSF Ricardian rents generally reflect the ability and inability, respectively, to take advantage of new agricultural possibilities in northern or alpine areas.

Effects of climatic change on equilibrium income from agricultural land are presented in Table VI. LUF agricultural land incomes indicate how climatic change might affect income from existing agricultural land under the assumption that agricultural and other production was confined to current land uses. ULUS agricultural

* This U-shape problem was cited as motivation for models presented in MNS (1996). A more detailed discussion of some of the econometric issues pertaining to MNS's cropland and crop revenue models can be found in Darwin (1998).

TABLE V

Effects of climatic change on Ricardian rents from agricultural land as simulated with FARM, by scenario and region[a]

Scenario[b]	Region: United States	Canada	EC	Japan	OEA[c]	SEA[d]	ANZ[e]	Rest of world
	Percent change							
Land-Use Fixed								
OSU	–9.99	8.54	–12.48	35.21	5.42	–14.79	13.79	–1.45
GFDL	–16.06	11.12	–18.53	39.33	12.45	–23.21	–1.85	–0.67
GISS	4.08	32.69	–21.60	33.87	5.32	–21.37	0.16	0.09
UKMO	–4.38	9.20	–21.22	44.65	–6.77	–34.45	–0.25	–2.17
Land-Use-Shares Fixed								
OSU	–6.67	110.73	–13.48	91.79	6.96	–4.34	11.50	7.32
GFDL	–7.34	172.95	–21.99	109.99	14.19	–10.25	–2.80	10.36
GISS	5.00	189.06	–25.70	91.58	9.55	–10.33	0.02	11.35
UKMO	1.14	304.01	–26.21	130.00	6.74	–16.01	–5.66	15.71

[a] Base incomes from agricultural land (in billions) are: U.S. – $25.4; Canada – $3.4; EC – $38.2; Japan – $17.8; OEA – $21.5; SEA – $8.9; ANZ – $3.9; and Rest of world – $105.4.
[b] Land-Use-Fixed scenarios assume that land-use patterns stay the same under global climatic change; Land-Use-Shares-Fixed scenarios assume that the proportions of land use within a given land class remain the same under global climatic change. Climate change scenarios are based on results from doubled atmospheric carbon dioxide levels as simulated by the general circulation models of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).
[c] Other East Asia (China, including Taiwan; Hong Kong; and South Korea).
[d] Southeast Asia (Thailand, Indonesia, Philippines, Malaysia, and Singapore).
[e] Australia and New Zealand.

land incomes indicate how climatic change might affect income from agricultural land if immediate supplies of agricultural and other land services were based on the assumption that shares of agricultural and other land services within a given land class were solely a function of climate. ALUS agricultural land incomes indicate how climatic change might affect agricultural landowners if immediate supplies of agricultural and other land services were equal to existing supplies of agricultural and other land services, and farmers and other economic agents adjusted their use of land services in response to additional economic changes. Regionally, LUF incomes are generally more positive or less negative than the ALUS income results and ALUS income results are generally more positive or less negative than the ULUS income results.

TABLE VI

Effects of climatic change on equilibrium income for agricultural land as simulated with FARM, by scenario and region[a]

Scenario[b]	Region							
	United States	Canada	EC	Japan	OEA[c]	SEA[d]	ANZ[e]	Rest of world
				Percent change				
Land-Use Fixed								
OSU	11.49	–2.32	14.31	–20.59	–1.72	11.72	–7.75	–1.36
GFDL	22.20	4.11	27.75	–21.22	–4.11	24.72	5.59	2.60
GISS	0.72	–10.27	30.44	–23.31	–5.82	20.05	6.83	–1.20
UKMO	12.80	7.59	36.66	–25.18	–0.91	38.52	5.22	3.03
Adjusted Land-Use Shares								
OSU	2.57	0.77	1.11	–27.08	–1.17	6.52	–12.99	–3.20
GFDL	6.72	2.52	3.64	–29.42	–2.82	14.27	–2.94	1.72
GISS	–2.98	–3.11	5.67	–28.07	–5.23	12.15	3.38	–1.13
UKMO	0.90	7.83	6.08	–34.68	–2.32	21.30	–3.48	0.00
Unadjusted Land-Use Shares								
OSU	0.37	–30.35	2.60	–39.47	–5.79	0.15	–7.57	–2.67
GFDL	–1.16	–38.32	7.43	–43.72	–6.79	4.92	–0.64	–2.50
GISS	–5.05	–37.45	7.13	–39.53	–6.92	3.84	0.07	–5.77
UKMO	–3.44	–46.78	8.63	–48.63	–3.78	8.16	1.56	–5.36

[a] Base incomes from agricultural land (in billions) are: U.S. – $25.4; Canada – $3.4; EC – $38.2; Japan – $17.8; OEA – $21.5; SEA – $8.9; ANZ – $3.9; and Rest of world – $105.4.
[b] Land-use-fixed scenarios assume that land-use patterns stay the same under global climatic change; Adjusted-Land-Use-Shares scenarios assume that current land-use patterns best define the initial conditions under global climatic change; Unadjusted-Land-Use-Shares scenarios assume that constant proportions of land use within a given land class be st de fine the initial conditions under global climatic change. Climatic change scenarios are based on results from doubled atmospheric carbon dioxide levels as simulated by the general circulation models of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).
[c] Other East Asia (China, including Taiwan; Hong Kong; and South Korea).
[d] Southeast Asia (Thailand, Indonesia, Philippines, Malaysia, and Singapore).
[e] Australia and New Zealand.

LUF incomes generally increase in the U.S., European Community, southeast Asia, and Australia/New Zealand, and generally decrease in Japan and other east Asia. Results are mixed in Canada and Rest-of-World. ALUS incomes generally increase in the U.S., Canada, European Community, and southeast Asia, and generally decrease in Japan, other east Asia, and Australia/New Zealand. Results are mixed in the Rest-of-World. ULUS incomes generally increase in the European Community and southeast Asia, and generally decrease in the U.S., Canada, Japan, other east Asia, and Rest-of-World. Results are mixed in Australia/New Zealand.

LUF Ricardian rents are compared with LUF and ALUS agricultural land incomes. Paired-sample t-tests of regional LUF and ALUS incomes minus regional LUF Ricardian rents for all regions and scenarios produce t_{31} equal to 0.58 and –0.49, respectively. These results indicate that the mean change in LUF Ricardian rents is statistically equal to the mean changes in LUF and ALUS incomes when all regions and scenarios are collectively considered.

A two-way ANOVA of differences between regional LUF Ricardian rents and LUF incomes (i.e., LUF income minus LUF Ricardian rent), however, yields $F_{3,21}$ and $F_{7,31}$ values equal to 2.43 and 30.03^{***} for scenarios and regions, respectively. These results indicate that the mean difference between LUF Ricardian rents and LUF incomes varies by region but not by scenario. Differences for Canada, Japan, and other east Asia, for example are generally negative, while differences for the U.S., European Community, southeast Asia, Australia/New Zealand, and Rest-of-World are generally positive.

Similarly, a two-way ANOVA of differences between regional LUF Ricardian rents and ALUS incomes (i.e., ALUS income minus LUF Ricardian rent) yields $F_{3,21}$ and $F_{7,21}$ values equal to 1.06 and 42.46^{***} for scenarios and regions, respectively. These results indicate that the mean difference between LUF Ricardian rents and ALUS incomes also varies by region but not by scenario. In this case, differences for Canada, Japan, other east Asia, and Australia/New Zealand are generally negative, while differences for the U.S., European Community, southeast Asia, and Rest-of-World are generally positive.

The signs of only 19 and 25% of the changes in LUF and ALUS incomes, respectively, match those of the changes in LUF Ricardian rents. Calculated χ_1^2 statistics (with Yate's correction) comparing the number of sign matches between LUF Ricardian rents and LUF and ALUS incomes are 10.10^{**} and 6.06^{*}, respectively. These results indicate that changes in LUF Ricardian rents and changes in LUF and ALUS incomes not only have dissimilar signs but have opposite signs. Calculated r_{30} of LUF Ricardian rents with LUF and ALUS incomes are -0.934^{***} and -0.880^{***}, respectively. These results indicate that LUF Ricardian rents are negatively correlated with LUF and ALUS income. The sign patterns and negative correlations combined mean that increases in LUF Ricardian rents on agricultural land are good indicators that the actual incomes of agricultural landowners are likely to decline.

LUSF Ricardian rents are compared with ULUS agricultural land incomes. A paired-sample t-test of regional ULUS income minus regional LUSF Ricardian rents yields t_{31} equal to -2.83^{**}. This result indicates that the mean change in ULUS incomes is statistically smaller than the mean change in LUSF Ricardian rents when all regions and scenarios are collectively considered.

A two-way ANOVA of regional differences yields $F_{3,21}$ and $F_{7,21}$ values equal to 0.96 and 32.25^{***} for scenarios and regions, respectively. These results indicate that the mean difference between LUSF Ricardian rents and ULUS varies by region but not by scenario. In this case, differences for Canada, Japan, other east Asia, and Rest-of-World are generally negative, while differences for the European Community, southeast Asia, and Australia/New Zealand are generally positive.

The signs of only 9% of the changes in ULUS incomes match those of the changes in LUSF Ricardian rents. The calculated χ_1^2 statistic (with Yate's correction) comparing the number of sign matches between LUSF Ricardian rents and ULUS incomes is 17.08^{***}. This indicates that changes in LUSF Ricardian rents have opposite signs as changes in ULUS incomes. The calculated r_{30} of LUSF Ricardian rents with ULUS incomes is -0.902^{***}, an indication of negative correlation. The sign pattern and negative correlation combined mean that increases in LUSF Ricardian rents on agricultural land are good indicators that the incomes of agricultural landowners would likely decline if the underlying ULUS assumptions were valid.

3.2.2. *Regional Welfare*

Impacts of four climatic change scenarios on Ricardian expenditures are presented in Table VII. LUF Ricardian expenditures indicate how climatic change might affect income if all land remained in its current use. LUSF Ricardian expenditures indicate how climatic change might affect income if the shares of all land uses within a given land class were solely a function of climate. Regionally, LUSF Ricardian expenditures are generally more positive or less negative than the LUF Ricardian expenditures. With two exceptions, changes in LUF and LUSF Ricardian expenditure have the same signs as changes in LUF and LUSF Ricardian rents on agricultural land. This is because income from agricultural land is a major component of income from all land.

Effects of climatic change on equilibrium expenditures are presented in Table VIII. LUF equilibrium expenditures indicate how climatic change might affect EV under the assumption that all production was confined to its existing land. ALUS equilibrium expenditures indicate how climatic change might affect EV if immediate supplies of agricultural and other land services were equal to existing supplies of land services, but farmers and other economic agents can adjust their use of land in response to additional economic changes. ULUS equilibrium expenditures indicate how climatic change might affect EV if immediate supplies of agricultural and other land services were based on the assumption that shares of land uses within a given land class were solely a function of climate.

TABLE VII

Effects of climatic change on Ricardian expenditures as simulated with FARM, by scenario and region[a]

Scenario[b]	Region								
	United States	Canada	EC	Japan	OEA[c]	SEA[d]	ANZ[e]	Rest of world	World total[f]
					Percent change				
Land-Use Fixed									
OSU	–0.05	0.16	–0.08	0.35	0.30	–0.46	0.15	–0.03	0.03
GFDL	–0.08	0.27	–0.13	0.40	0.59	–0.74	–0.03	–0.02	0.07
GISS	0.04	0.43	–0.14	0.34	0.40	–0.68	0.00	0.02	0.06
UKMO	0.00	0.40	–0.14	0.45	0.10	–1.10	–0.01	–0.04	–0.06
Land-Use-Shares Fixed									
OSU	–0.03	0.66	–0.09	0.75	0.22	–0.18	0.14	0.16	0.14
GFDL	–0.04	1.03	–0.14	0.90	0.44	–0.41	–0.03	0.21	0.21
GISS	0.04	1.15	–0.16	0.75	0.30	–0.41	0.00	0.26	0.21
UKMO	0.01	1.83	–0.16	1.07	0.21	–0.64	–0.07	0.33	0.22

[a] Changes in Ricardian expenditures are equivalent to changes in Ricardian rents on all land. Base expenditures (in billions) are: U.S. – $5,496.6; Canada – $597.8; EC – $5,923.3; Japan – $3,041.4; OEA – $743.4; SEA – $292.0; ANZ – $361.9; and Rest of world – $4,602.8.
[b] Land-Use-Fixed scenarios assume that land-use patterns stay the same under global climatic change; Land-Use-Shares-Fixed scenarios assume that the proportions of land use within a given land class remain the same under global climatic change. Climate change scenarios are based on results from doubled atmospheric carbon dioxide levels as simulated by the general circulation models of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).
[c] Other East Asia (China, including Taiwan; Hong Kong; and South Korea).
[d] Southeast Asia (Thailand, Indonesia, Philippines, Malaysia, and Singapore).
[e] Australia and New Zealand.
[f] Population-weighted percent change. Regional populations (in millions) are: U.S. – 248.9; Canada – 26.6; EC – 344.0; Japan – 123.5; OEA – 1,177.4; SEA – 319.3; ANZ – 20.5; and Rest of world – 3,032.9. Calculated from information in World Resources Institute, 1990.

LUF expenditures generally increase in Canada, Japan, and Australia/New Zealand, and generally decrease in the U.S., European Community, other east Asia and southeast Asia. Results are mixed in the Rest-of-World. ALUS expenditures generally increase in Canada, Japan, and Australia/New Zealand, and generally decrease in the European Community, southeast Asia, and Rest-of-World. Results are mixed in the U.S. and other east Asia. ULUS expenditures generally increase in Canada, Japan, other east Asia, and Rest-of-World, and generally decrease in

TABLE VIII

Effects of climatic change on equilibrium expenditures as simulated with FARM, by scenario and region[a]

Scenario[b]	Region								
	United States	Canada	EC	Japan	OEA[c]	SEA[d]	ANZ[e]	Rest of world	World total[f]
	Percent change								
Land-Use Fixed									
OSU	–0.06	0.08	–0.09	0.09	–0.15	–0.55	0.26	–0.02	–0.08
GFDL	–0.12	0.07	–0.18	0.07	–0.11	–0.87	0.07	0.02	–0.08
GISS	0.04	0.28	–0.17	0.16	0.03	–0.96	0.16	0.01	–0.05
UKMO	–0.02	0.16	–0.25	0.10	–0.35	–1.65	0.16	–0.06	–0.23
Adjusted Land-Use Shares									
OSU	–0.04	0.03	–0.02	0.07	–0.03	–0.42	0.18	–0.05	–0.06
GFDL	–0.08	–0.01	–0.08	0.04	0.09	–0.53	–0.03	0.03	0.00
GISS	0.03	0.19	–0.07	0.11	0.11	–0.60	0.12	–0.01	–0.01
UKMO	0.03	0.10	–0.12	0.03	–0.07	–1.00	0.08	–0.05	–0.11
Unadjusted Land-Use Shares									
OSU	–0.02	0.26	–0.01	0.25	0.10	–0.18	0.11	0.13	0.09
GFDL	–0.05	0.30	–0.06	0.29	0.31	–0.29	–0.08	0.19	0.16
GISS	0.02	0.36	–0.04	0.20	0.24	–0.32	0.02	0.22	0.16
UKMO	0.00	0.41	–0.08	0.33	0.31	–0.55	–0.10	0.23	0.17

[a] Changes in expenditures are equal to equivalent variation (EV). Base expenditures (in billions) are: U.S. – $5,496.6; Canada – $597.8; EC – $5,923.3; Japan – $3,041.4; OEA – $743.4; SEA – $292.0; ANZ – $361.9; and Rest of World – $4,602.8.

[b] Land-Use-Fixed scenarios assume that land-use patterns stay the same under global climate change; Adjusted-Land-Use-Shares scenarios assume that current land-use patterns best define the initial conditions under global climatic change; Unadjusted-Land-Use-Shares scenarios assume that constant proportions of land use within a given land class best define the initial conditions under global climatic change. Climatic change scenarios are based on results from doubled atmospheric carbon dioxide levels as simulated by the general circulation models of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).

[c] Other East Asia (China, including Taiwan; Hong Kong; and South Korea).

[d] Southeast Asia (Thailand, Indonesi, Philippines, Malaysia, and Singapore).

[e] Australia and New Zealand.

[f] Population-weighted percent change. Regional populations (in millions) are: U.S. – 248.9; Canada – 26.6; EC – 344.0; Japan – 123.5; OEA – 1,177.4; SEA –319.3; ANZ – 20.5; and Rest of World – 3,032.9. Calculated from information in World Resources Institute, 1990.

the European Community and southeast Asia. Results are mixed in the U.S. and Australia/New Zealand.

Regionally, ALUS expenditures are generally more positive or less negative than LUF expenditures. This reflects the benefits of allowing agricultural and other producers to modify their use of land services, especially in northern and alpine areas. Also, ULUS expenditures are generally more positive or less negative than ALUS expenditures. This reflects the benefits of allowing agricultural and other producers to take advantage of new production possibilities in northern or alpine areas without regard to current land-use patterns or non-climatic factors in these areas.

LUF Ricardian expenditures are compared with LUF and ALUS equilibrium expenditures. Paired-sample t-tests of regional LUF and ALUS equilibrium expenditures minus regional LUF Ricardian expenditures yield t_{31} equal to -3.82^{***} and -2.55^{*}, respectively. These results indicate that the mean changes in LUF and ALUS equilibrium expenditures are statistically smaller than the mean change of LUF Ricardian expenditures when all regions and scenarios are collectively considered.

A two-way ANOVA of differences between regional LUF Ricardian expenditures and LUF equilibrium expenditures (i.e., LUF equilibrium expenditures minus LUF Ricardian expenditures) yields $F_{3,21}$ and $F_{7,21}$ values equal to 2.01 and 18.26^{***} for scenarios and regions, respectively. These results indicate that the mean difference between LUF Ricardian expenditures and LUF equilibrium expenditures vary by region but not by scenario. Differences for the U.S., Canada, European Community, Japan, other east Asia, and southeast Asia are generally negative, while differences for Australia/New Zealand are generally positive. Results are mixed in the Rest-of-World.

A two-way ANOVA of differences between regional LUF Ricardian expenditures and ALUS equilibrium expenditures (i.e, ALUS equilibrium expenditures minus LUF Ricardian expenditures) yields $F_{3,21}$ and $F_{7,21}$ values equal to 0.35 and 22.86^{***} for scenarios and regions, respectively. These results indicate that the mean difference between LUF Ricardian expenditures and ALUS equilibrium expenditures vary by region but not by scenario. Differences for Canada, Japan, other east Asia, and Rest-of-World are generally negative, while differences for the U.S., European Community, southeast Asia, and Australia/New Zealand are generally positive.

The signs of 78 and 88% of the changes in LUF and ALUS equilibrium expenditures, respectively, match those of the changes in LUF Ricardian expenditures. Calculated χ^2_1 statistics (with Yate's correction) comparing the number of sign matches between LUF Ricardian expenditures and LUF and ALUS equilibrium expenditures are 8.03^{**} and 15.21^{***}, respectively. These results indicate that changes in LUF Ricardian expenditures have the same signs as changes in LUF and ALUS equilibrium expenditures. Calculated r_{30} of LUF Ricardian expenditures with LUF and ALUS equilibrium expenditures are 0.852^{***} and 0.895^{***}, respectively. These results indicate that LUF Ricardian expenditures are positively correlated with LUF and ALUS expenditures. The sign pattern and positive correlation combined mean that increases in regional LUF Ricardian expenditures (or Ricardian rents on all land) are good indicators that regional equilibrium expenditures (or EV) are likely to increase.

LUSF Ricardian expenditures are compared with ULUS equilibrium expenditures. A paired-sample t-test of regional ULUS equilibrium expenditures minus LUSF Ricardian expenditures yields t_{31} equal to –3.04**. This result indicates that the mean changes in ULUS equilibrium expenditures are statistically smaller than the mean change of LUSF Ricardian expenditures when all regions and scenarios are collectively considered.

A two-way ANOVA of regional differences (i.e., ULUS equilibrium expenditures minus LUSF Ricardian expenditures) yields $F_{3,21}$ and $F_{7,21}$ values equal to 0.87 and 12.23*** for scenarios and regions, respectively. These results indicate that the mean difference between LUSF Ricardian expenditures and ULUS equilibrium expenditures vary by region but not by scenario. Differences for the U.S., Canada, Japan, other east Asia, Australia/New Zealand, and Rest-of-World are generally negative, while differences for the European Community and southeast Asia are generally positive.

Signs of the changes in ULUS equilibrium expenditures and the changes in LUSF Ricardian expenditures match in all cases. The calculated χ_1^2 statistic (with Yate's correction) comparing the number of sign matches between LUSF Ricardian expenditures and ULUS equilibrium expenditures is 27.88***. The calculated r_{30} of LUSF Ricardian expenditures with ULUS equilibrium expenditures is 0.860***, indicating a positive correlation. The sign pattern and positive correlation combined mean that increases in regional LUSF Ricardian expenditures are good indicators that regional ULUS equilibrium expenditures are likely to increase.

3.2.3. *World Welfare*

With one exception, changes in world LUF and LUSF Ricardian expenditures are positive, ranging from –0.06 to 0.07% per capita. Changes in world LUF and ALUS equilibrium expenditures are generally negative, ranging from –0.23 to –0.05 and from –0.11 to 0.00% per capita, respectively. Changes in world ULUS equilibrium expenditures are positive, ranging from 0.09 to 0.17% per capita. Paired-sample t-tests of world LUF and ALUS equilibrium expenditures minus world LUF Ricardian expenditures yield t_3 equal to –8.49** and –8.08**, respectively. A paired-sample t-test of world ULUS equilibrium expenditures minus world LUSF Ricardian expenditures yield t_3 equal to –13.14***. These results indicate that changes in world equilibrium expenditures are smaller than changes in world Ricardian expenditures.

Calculated r_2 of LUF Ricardian expenditures with LUF and ALUS equilibrium expenditures are 0.957* and 0.968*, respectively. These results indicate that LUF Ricardian expenditures are positively correlated with LUF and ALUS equilibrium expenditures. The signs of the changes in LUF Ricardian expenditures, however, do not match the signs of the changes in LUF and ALUS equilibrium expenditures. This means that increases in world LUF Ricardian expenditures are not good indicators that world equilibrium expenditures will increase.

The calculated r_2 of LUSF Ricardian results with ULUS equilibrium results is 0.994**. This result indicates that LUSF Ricardian expenditures are positively correlated with ULUS equilibrium expenditures. In addition, the signs of the changes in LUSF Ricardian expenditures match the signs of the changes in ULUS equilibrium expenditures. This means that increases in world LUSF Ricardian expenditures are good indicators that world ULUS equilibrium expenditures would also increase.

3.2.4. *Discussion*

It is clear from the negative correlations and opposite signs that regional changes in Ricardian rents on agricultural land are poor *quantitative* measures of how global climatic change is likely to affect the welfare of agricultural landowners. Changes in Ricardian rents on agricultural land can be used as *qualitative* measures of changes in agricultural landowners' welfare, however, *if one recognizes that increases in Ricardian rents actually indicate losses in landowner welfare on average and vice versa*. That agricultural landowners (primarily producers) benefit in scenarios that simulate climate-induced declines in agricultural productivity is not a peculiarity of FARM. It is also consistent with results presented by Adams et al. (1995). In model runs with no additional CO_2 fertilization effect, with current export demand, and with decreases in U.S. agricultural production of 5, 8, and 25% for the GISS, GFDL, and UKMO scenarios, respectively, welfare of U.S. producers increased by 10.8, 16.8, and 115.0 billion dollars, respectively.

In effect, benefits and losses associated with positive and negative changes in Ricardian rents are passed on to consumers. The value of agricultural services from land, for example, increases in regions where climatic change causes the supply of those services to decline. At the same time, more land is required to produce a given amount of agricultural product. Owners of agricultural land services, therefore, are better off than they were before. Consumers, on the other hand, have to pay more for the goods and services in which agricultural services from land compose a relatively large component. Hence they are worse off than they were before. The opposite occurs in regions where agricultural services from land become more prevalent.

It is also clear from the positive correlations and similar signs that regional changes in Ricardian rents on all land are good *qualitative* measures of changes in regional welfare. Results from the two-way ANOVA's and paired-sample t-tests, however, indicate that regional changes in Ricardian rents on all land are poor *quantitative* measures of regional welfare changes. A closer examination of the two-way ANOVA results is also revealing. A comparison of ALUS and LUF differences (i.e., ALUS equilibrium expenditures minus LUF Ricardian expenditures) with LUF Ricardian expenditures, for example, shows that the signs of the differences have opposite signs of the base values in 88% of the observations. Canada's LUF Ricardian expenditures, for example, are positive, but its ALUS/LUF differences are negative. Similarly, southeast Asia's LUF Ricardian expenditures are negative, but its ALUS/LUF differences are positive. A comparison of ULUS and LUSF differences with LUSF Ricardian rents reveals the same phenomenon. This indicates that regional changes in Ricardian expenditures systematically overestimate both benefits and losses.

At the same time, the paired-sample t-test results indicate that regional changes in Ricardian rents on all land are, on average, upwardly biased with respect to regional welfare. This is also supported by the fact that overestimates of regional benefits are consistently larger than overestimates of regional losses. The ratio of ALUS equilibrium expenditure changes to LUF Ricardian expenditure changes when Ricardian changes indicate benefits is 0.20. The ratio of ALUS equilibrium expenditure changes to LUF Ricardian expenditure changes when Ricardian changes indicate losses is 0.80. Similar ratios for changes in ULUS equilibrium and LUSF Ricardian expenditures are 0.41 and 0.75 for benefits and losses, respectively.

Factors responsible for the quantitatively poor mapping of regional changes in Ricardian rents on all land to regional economic welfare include (1) sticky (or 'inelastic') household demand for land-intensive commodities, (2) input constraints, (3) international trade, and (4) price changes. Quantities of land-intensive commodities like food and forestry products demanded by households will not expand or contract at the rates implied by changes in Ricardian rents. Consumption of these commodities remains fairly constant for a given level of income. During shortages, for example, households will readily pay higher prices to maintain their food intake, but during gluts, households will not buy more food than they need even at very low prices. This reduces the incentive for producers to expand or reduce production of these goods and services even though climatic change may increase or decrease their ability to do so. Changes in Ricardian rents do not account for such household behavior.

Input quantities likewise will not expand or contract at rates implied by changes in Ricardian rents. Under Ricardian assumptions one implicitly assumes that most inputs are either readily available at current prices or that they simply vanish into thin air. In the real world, inputs are relatively fixed. This means that farmers in regions with greater agricultural opportunities on existing agricultural land may increase production, but can do so only by obtaining inputs from other sectors. Agricultural production may increase, for example, but only if forestry production declines. In regions where decreases in Ricardian rents indicate fewer agricultural opportunities, the labor and capital available to farmers and other economic agents remains unchanged. Their availability lessens the negative impacts implied by falling Ricardian rents, which only measure changes in productive services from land.

International trade tends to shift damages from regions with relatively high losses to regions with relatively low, no, or negative losses. Although moderated by regional differences in comparative advantage and the importance of trade as a source of income, this effect also contributes to the tendency of changes in Ricardian rents to overestimate benefits and losses. Price changes, on the other hand, work in the opposite direction. Recall that EV represents the price-adjusted welfare impact of some event. If an event's consequences are negative overall, then prices will rise, which will, in turn, generate additional welfare losses because consumers will have to spend more of their income to purchase the same quantity of goods and services as before the event. If an event's consequences are positive overall, then prices will fall and consumers will be able to spend less of their income for a given quantity of goods and services.

The actual result depends upon the strength of the competing tendencies given the simulation assumptions. In the ALUS and ULUS cases, where adjustments in the use of land services by economic agents are simulated, the effects of price changes are more than offset by the effects of sticky household demand, input constraints, and international trade. In the LUF equilibrium case, however, changes in Ricardian rents tend to underestimate losses in the U.S., European Community, and southeast Asia, as well as underestimate benefits in Australia/New Zealand and Rest-of-World. The underlying reason is the unrealistic restriction on the ability of economic agents to adjust their use of land services. Farmers in Canada, Japan, and other east Asia cannot take full advantage of new agricultural opportunities. This inhibits the overall moderating effect of international trade and enhances the negative impacts of higher prices in the U.S., European Community, and southeast Asia. Lower than expected supplies of agricultural products from Canada and the resultant higher prices also contribute to the underestimation of benefits in Australia/New Zealand and Rest-of-World. Food exports are a relatively large share of income in these two regions. The additional income generated by greater than expected export sales at higher prices helps to offset losses (or enhance benefits) generated by climatic change in these regions.

As outlined above, regional changes in Ricardian rents on all land may differ from changes in regional welfare because of trade-induced leakages to (or from) other regions. Comparing changes in Ricardian rents on all the world's land with changes in total world welfare controls for trade-induced leakages. Results from the paired-sample t-tests indicate that changes in Ricardian rents on all the world's land are poor *quantitative* measures of changes in world welfare. Dissimilar signs coupled with positive correlations indicate that changes in LUF Ricardian rents on all the world's land are poor *qualitative* measures of changes in LUF and ALUS world welfare as well. Similar signs and positive correlation indicate that changes in LUSF Ricardian rents on all the world's land are good *qualitative* measures of changes in ULUS world welfare. These results do not change when dollar sums are substituted for population-weighted percent changes in per capita utility in the analysis.

Finally, global declines in LUF equilibrium expenditures reported here are similar to the 'land-use-fixed' results presented in Darwin et al. (1995). The current global increases in ULUS equilibrium expenditure, on the other hand, are on balance more positive than Darwin et al.'s 'land-use-flexible' results, two of which were negative. Neither set of cases is very satisfactory. LUF cases are too pessimistic because economic agents are forced to stay at their current locations, while ULUS cases are too optimistic because important non-climatic constraints are ignored. ALUS cases fall somewhere in the middle. The ALUS declines in world welfare imply that climatic changes induced by a doubling of CO_2 might push the average global temperature past an agricultural optimum. Various limitations in this research need to be addressed, however, before a definitive conclusion can be reached. This research, for example, does not include the beneficial effects of greater concentrations of atmospheric CO_2 on plant growth. It also does not account for potential future economic conditions.

3.3. APPLICATION

In this section, estimated changes in Ricardian rents in the former Soviet Union, eastern and northern Europe, western and southern Asia, Latin America, and Africa are presented. Their welfare implications are evaluated in light of the knowledge attained in Section 3.2.

3.3.1. *Rents on Agricultural Land*

Except for the former Soviet Union, percent changes in LUF Ricardian rents on agricultural land are generally negative (see Table IX). Percent changes in LUSF Ricardian rents on agricultural land are, with minor exceptions, generally positive. The most positive changes are in areas at high latitudes – the former Soviet Union and eastern and northern Europe. This is consistent with aggregate Rest-of-World estimates (see Table V), which are generally negative for the LUF cases and positive for the LUSF cases.

3.3.2. *Regional Expenditures*

Changes in Ricardian expenditures generally have the same signs as changes in Ricardian rents on agricultural land (Table X). The only exceptions are in Africa, where changes in LUSF Ricardian expenditures indicate losses in two cases, while changes in LUSF Ricardian rents on agricultural land indicate only benefits. For the Rest-of-World as a whole, changes in Ricardian expenditure range from −0.14 to 0.00% and from 0.12 to 0.31%, respectively, for the LUF and LUSF cases. These 'disaggregated' Rest-of-World results differ from those presented in Table VII. Three disaggregated LUF results are more negative and three disaggregated LUSF results are less positive than their corresponding aggregated results. The largest differences occur in the UKMO climate scenario. Disaggregated results are less negative or more positive than the aggregated results in the GFDL climate

TABLE IX

Effects of climatic change on Ricardian rents on agricultural land in major subregions of FARM's Rest-of-World Region as simulated with FARM

Scenario[a]	Region				
	Former Soviet Union[b]	Eastern and Northern Europe[c]	Western and Southern Asia[d]	Latin America	Africa
	Percent change				
Land-Use Fixed					
OSU	1.74	–7.90	–1.95	–1.23	–2.53
GFDL	2.95	–15.14	1.67	–2.97	–1.53
GISS	7.19	3.95	–3.82	–2.30	–0.76
UKMO	3.89	–2.45	–6.57	–1.52	–3.18
Land-Use-Shares Fixed					
OSU	30.25	4.69	2.86	0.50	4.21
GFDL	47.94	1.82	13.74	–0.82	1.66
GISS	55.57	35.09	6.08	0.34	0.83
UKMO	63.74	27.84	–0.23	–1.07	4.41

[a] Land-Use-Fixed scenarios assume that land-use patterns stay the same under global climatic change; Land-Use-Shares-Fixed scenarios assume that the proportions of land use within a given land class remain the same under global climatic change. Climate scenarios based on results from doubled atmospheric carbon dioxide levels as simulated by the general circulation models of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).
[b] Former Soviet Union also include Mongolia.
[c] Other Europe includes all Europe except the European Community as of 1990.
[d] Other Asia includes all Asia and Oceania except Japan, China (including Hong Kong and Taiwan), South Korea, Thailand, Indonesia, Philippines, Malaysia, Singapore, Australia, and New Zealand.

scenario, especially in the LUSF case. Results from paired-sample t-tests and product-moment correlations are not statistically significant. For the aggregated and disaggregated LUF results, $t_3 = 1.51$ and $r_2 = 0.413$. For the LUSF results, $t_3 = 0.59$ and $r_2 = -0.206$.

Results in Section 3.2.2 show that changes in Ricardian expenditures overestimate equilibrium benefits and losses. To estimate equilibrium benefits and losses, I multiplied the positive and negative changes in disaggregated LUF Ricardian expenditures by 0.20 and 0.80, respectively. Positive and negative changes in disaggregated LUSF Ricardian expenditures were multiplied by 0.41 and 0.75, respectively (Table XI). For the Rest-of-World as a whole, results range from

TABLE X

Effects of climatic change on Ricardian expenditures in major subregions of FARM's Rest-of-World Region and for the world as simulated with FARM[a]

Scenario[b]	Region					
	Former Soviet Union[c]	Eastern and Northern Europe[d]	Western and Southern Asia[e]	Latin America	Africa	Rest of World[f]
			Percent change			
Land-Use Fixed						
OSU	0.04	–0.14	–0.05	–0.03	–0.08	–0.05
GFDL	0.06	–0.28	0.08	–0.11	–0.08	0.00
GISS	0.18	0.09	–0.10	–0.06	–0.04	–0.05
UKMO	0.12	–0.02	–0.23	–0.06	–0.14	–0.14
Land-Use-Shares Fixed						
OSU	0.50	0.09	0.11	0.01	0.12	0.13
GFDL	0.82	0.04	0.50	–0.07	–0.04	0.31
GISS	1.00	0.65	0.23	0.01	–0.02	0.24
UKMO	1.12	0.52	–0.01	–0.08	0.04	0.12

[a] Changes in Ricardian expenditures are equivalent to changes in Ricardian rents on all land. Percent changes in Ricardian expenditures were calculated using aggregate land values for FARM's rest-of-world region. To adjust these percent changes of expenditures based only on land income to percent changes in total expenditures, Ricardian estimates in the former Soviet Union and other Europe were multiplied by 0.020, while Ricardian estimates in other Asia, Latin America, and Africa were multiplied by 0.038.

[b] Land-Use-Fixed scenarios assume that land-use patterns stay the same under global climatic change; Land-Use-Shares-Fixed scenarios assume that the proportions of land use within a given land class remain the same under global climatic change. Climate scenarios based on results from doubled atmospheric carbon dioxide levels as simulated by the general circulation models of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).

[c] Former Soviet Union also includes Mongolia.

[d] Eastern and Northern Europe includes Greenland and all Europe except the European Community as of 1990.

[e] Western and Southern Asia includes all Asia and Oceania except Japan, China (including Hong Kong and Taiwan), South Korea, Thailand, Indonesia, Philippines, Malaysia, Singapore, Australia, and New Zealand.

[f] Population-weighted percent change. Regional populations (in millions) are: former Soviet Union – 290.2; other Europe – 153.7; other Asia – 1492.1; Latin America – 448.5; and Africa – 647.5. Calculated from information in World Resources Institute, 1990.

TABLE XI

Modified Ricardian expenditures in major subregions of FARM's Rest-of-World Region and for the world[a]

Scenario[b]	Region					
	Former Soviet Union[c]	Eastern and Northern Europe[d]	Western and Southern Asia[e]	Latin America	Africa	Rest of World[f]
			Percent change			
Land-Use Fixed						
OSU	0.01	–0.11	–0.04	–0.02	–0.06	–0.04
GFDL	0.01	–0.22	0.02	–0.09	–0.07	–0.03
GISS	0.04	0.02	–0.08	–0.05	–0.03	–0.05
UKMO	0.02	–0.02	–0.18	–0.04	–0.11	–0.12
Land-Use-Shares Fixed						
OSU	0.21	0.04	0.04	0.00	0.05	0.05
GFDL	0.34	0.02	0.21	–0.05	–0.03	0.12
GISS	0.41	0.27	0.09	0.00	–0.02	0.10
UKMO	0.46	0.21	–0.01	–0.06	0.02	0.04

[a] Changes in Ricardian expenditures are equivalent to changes in Ricardian rents on all land. Percent changes in Ricardian expenditures were calculated using aggregate land values for FARM's rest-of-world region. To adjust these percent changes of expenditures based only on land income to percent changes in total expenditures, Ricardian estimates in the former Soviet Union and other Europe were multiplied by 0.020, while Ricardian estimates in other Asia, Latin America, and Africa were multiplied by 0.038. Overestimations of benefits and losses are corrected by multiplying LUF Ricardian expenditures by 0.20 and 0.80 and LUSF Ricardian expenditures by 0.41 and 0.75, respectively, when benefits and losses are indicated.

[b] Land-Use-Fixed scenarios assume that land-use patterns stay the same under global climatic change; Land-Use-Shares-Fixed scenarios assume that the proportions of land use within a given land class remain the same under global climatic change. Climate scenarios based on results from doubled atmospheric carbon dioxide levels as simulated by the general circulation models of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).

[c] Former Soviet Union also includes Mongolia.

[d] Eastern and Northern Europe includes Greenland and all Europe except the European Community as of 1990.

[e] Western and Southern Asia includes all Asia and Oceania except Japan, China (including Hong Kong and Taiwan), South Korea, Thailand, Indonesia, Philippines, Malaysia, Singapore, Australia, and New Zealand.

[f] Population-weighted percent change. Regional populations (in millions) are: former Soviet Union – 290.2; other Europe – 153.7; other Asia – 1492.1; Latin America – 448.5; and Africa – 647.5. Calculated from information in World Resources Institute, 1990.

–0.12 to –0.03% and from 0.04 to 0.12%, respectively, for the LUF and LUSF cases. These modified Ricardian expenditures are generally more negative or less positive than their corresponding ALUS and ULUS equilibrium expenditures (Table VIII). Comparisons of the modified LUF Ricardian expenditures with the ALUS Rest-of-World equilibrium expenditures yield $t_3 = 2.12$ and $r_2 = 0.597$. Comparisons of the modified LUSF Ricardian expenditures with the ULUS Rest-of-World equilibrium expenditures yield $t_3 = 3.98^*$ and $r_2 = 0.158$.

3.3.3. *World Expenditures*

To estimate the effects of these changes on world welfare, I substituted modified LUF and LUSF Rest-of-World Ricardian expenditures for ALUS and ULUS Rest-of-World equilibrium expenditures, respectively, and recalculated population-weighted percent changes in world per capita utility. Modified per capita changes in world welfare for the ALUS simulations are –0.06, –0.04, –0.04, and –0.15%, respectively, for the OSU, GFDL, GISS, and UKMO scenarios. Modified per capita changes in world welfare for the ULUS simulations are 0.05, 0.12, 0.10, and 0.06%, respectively, for the OSU, GFDL, GISS, and UKMO scenarios. Modified changes in world welfare are more negative or less positive than corresponding unmodified changes in world welfare (Table VIII). Comparisons of modified and unmodified changes in ALUS world welfare yield $t_3 = 2.74$ and $r_2 = 0.933$. Comparisons of modified and unmodified changes in ULUS world welfare yield $t_3 = 3.57^*$ and $r_2 = 0.559$.

3.3.4. *Discussion*

Percent changes in LUF Ricardian rents on agricultural land indicate that climatic change would reduce productivity on existing agricultural land in areas that straddle the equator (e.g., Latin America and Africa) and increase productivity on existing agricultural land in areas at high latitudes (e.g., the former Soviet Union). Impacts on existing agricultural land in other areas are mixed. This is consistent with results for southeast Asia and Canada presented in Table V as well as with previously published results (Rosenzweig and Parry, 1994; Darwin et al., 1995). The generally positive percent changes in LUSF Ricardian rents on agricultural land indicate that any detrimental effects of climate change on existing agriculture might be offset somewhat (while beneficial effects may be enhanced somewhat) in Rest-of-World areas, if farmers can take advantage of new, climate-induced, agricultural opportunities on what are currently non- agricultural lands. Recall that results in Section 3.2.2 show that on average consumers, not owners of agricultural land, will receive the indicated losses and benefits.

Percent changes in LUF Ricardian expenditures indicate that climatic change would likely have detrimental, beneficial, and mixed effects on economic welfare in, respectively, equatorial, high latitude, and other areas in FARM's Rest-of-World region. Percent changes in LUSF Ricardian expenditures also indicate that new opportunities might moderate some of the detrimental impacts. Aggregated and disaggregated changes in Ricardian expenditures for the Rest-of-World as a whole have different signs in some instances and are not statistically correlated. I consider this part of a more general aggregation problem whereby the geographical scale of the Rest-of-World region conceals too many important differences among areas and leads to imprecise results.

The Rest-of-World aggregation problem probably leads to upwardly biased results from FARM's CGE model as well. Results from the paired-sample t-tests of modified LUF and LUSF Ricardian expenditures and ALUS and ULUS equilibrium expenditures for FARM's Rest-of-World indicate that changes in ALUS equilibrium expenditures *may* underestimate losses ($t_3 = 2.12$ is almost statistically significant at the 10% level) and that changes in ULUS equilibrium expenditures are likely to overestimate benefits in this region. The upward bias in the Rest-of-World region is also reflected in world welfare. Results from the paired-sample t-tests of modified LUF and LUSF Ricardian expenditures and ALUS and ULUS equilibrium expenditures for the world as a whole indicate that changes in ALUS equilibrium expenditures *may* underestimate losses ($t_3 = 2.73$ is statistically significant at the 10% level) and that changes in ULUS equilibrium expenditures are likely to overestimate benefits.

Modified changes appear to be more consistent than unmodified changes with a hill-shaped relationship between average surface land temperature and world welfare. Modified ALUS results indicate that the welfare optimizing temperature is either already lower than the current average surface land temperature, or is between the current average surface land temperature and somewhat less than 3.0 °C higher. (The relationships between climate and Ricardian rents on agricultural land depicted in Table II tend to support the latter.) The implications of the unmodified ALUS results, on the other hand, are not very clear. Modified ULUS results indicate a welfare optimizing temperature about 4.5 °C higher than the current average surface land temperature. Unmodified ULUS results indicate a welfare optimizing temperature somewhat more than 6.0 °C higher than the current average surface land temperature.

4. Summary and Conclusions

Recent research by MNS (1994, 1996) indicates that direct estimates of climate-induced changes in Ricardian rents on agricultural land provide information about the economic value global climatic change. Darwin et al.'s (1994, 1995) FARM framework also provides estimates of climate-induced changes in Ricardian rents on agricultural and other land. FARM's changes in Ricardian rents on agricultural land are consistent with a hill-shaped relationship between temperature and agricultural land rents, a basic Ricardian tenet, and are, therefore, reasonable. FARM also estimates traditional measures of economic welfare – measures that would also account for the indirect interactions between farmers, other producers, and consumers generated by climatic change in various regions around the world. FARM, therefore, provides a consistent framework with which to evaluate changes in Ricardian rents as welfare measures.

The first major result of this evaluation is that regional changes in Ricardian rents on agricultural land are poor *quantitative* measures of how global climatic change is likely to affect the welfare of agricultural landowners. Changes in Ricardian rents on agricultural land can be used as *qualitative* measures of changes in agricultural landowners' welfare, however, *if one recognizes that increases in Ricardian rents actually indicate losses in landowner welfare and vice versa*. Benefits and losses associated with positive and negative changes in Ricardian rents on agricultural are passed on to consumers.

The second major result is that regional changes in Ricardian rents on all land are good *qualitative* measures of changes in regional welfare. Regional changes in Ricardian rents on all land are poor *quantitative* welfare measures because they systematically overestimate both benefits and losses. In addition, they are on average upwardly biased because inflated benefits are larger than exaggerated losses. Explanatory factors for these results include (1) sticky (or 'inelastic') household demand for land-intensive commodities, (2) input constraints, (3) international trade, and (4) price changes.

The third major result is that changes in Ricardian rents on all the world's land are poor *quantitative* measures of changes in world welfare. Changes in LUF Ricardian rents on all the world's land are poor *qualitative* measures of changes in LUF and ALUS world welfare as well. Changes in LUSF Ricardian rents on all the world's land are good *qualitative* measures of changes in ULUS world welfare. On balance, then, changes in Ricardian rents do not provide accurate information about the welfare implications of climatic change for agricultural landowners, for consumers in specific regions, or for consumers of the world as a whole. Analists, therefore, will continue to rely on more comprehensive models for this information.

Despite these shortcomings, changes in Ricardian rents can provide useful information when other measures are not available so long as their limitations are carefully considered. Changes in Ricardian rents in areas composing FARM's Rest-of-World region, for example, indicate that climatic change would likely have detrimental effects in Latin America and Africa, beneficial effects in the former Soviet Union, and either detrimental or beneficial impacts in eastern and northern Europe and western and southern Asia. This is consistent with previous studies showing that climatic change would likely have detrimental, beneficial, and mixed effects on economic welfare in, respectively, equatorial, high latitude, and temperate areas (Rosenzweig and Parry, 1994; Darwin et al., 1995). The Rest-of-World analysis also indicates that aggregate Ricardian measures are probably not suitable for this relatively large and diversified region and that equilibrium measures for the region are likely to be biased upward. The upward bias in Rest-of-World measures would be reflected in measures of world welfare as well.

Finally, because they are interesting in and of themselves, a few words about the equilibrium measures without reference to their Ricardian counterparts are in order. First, where compatible, changes in global welfare reported here are generally consistent with changes presented in Darwin et al. (1995). These changes confirm that pessimistic assumptions about our ability take advantage of potential new opportunities are associated with losses, while optimistic assumptions about both the size of and our ability to respond to potential new opportunities are associated with benefits. Results from new scenarios with moderately flexible land-use change and which take account of current land-use patterns, however, indicate that changes in temperature and precipitation induced by a doubling of CO_2 could cause global welfare to decline on average. Results from the new scenarios (combined with results from the Ricardian analysis of the Rest-of-World region) also indicate that world welfare may not decline and could even increase if the average surface land temperature does not increase by more than 1.0 °C or 2.0 °C. Increases of 3.0 °C or more, however, are likely to cause world welfare to decline.

A number of caveats about the Ricardian analysis are in order. First, magnitudes of the equilibrium welfare measures depend on the model parameters (i.e., elasticities of transformation of land services, elasticities of substitution of primary factors in the economic sectors, elasticities of transformation of crops, and elasticities of transformation among imported commodities and between imported and domestically produced commodities) of FARM's CGE model. Most parameters in FARM were obtained from a review of the literature. Important exceptions are the elasticities of transformation of land services. Increasing and decreasing these elasticities by 50%, however, cause world per capita utility to increase and decrease, respectively, by only 4%. Second, because FARM's CGE model is a comparative static model, it does not capture how changes in agricultural productivity might affect the availability of other primary factors of production over time. Such impacts would be relatively small given the rates of climatic change currently expected over the next 50 to 100 years. Third, Ricardian measures in the Rest-of-World analysis are based on land values and income shares that are relatively uncertain. More precise information about these variables would lead to modifications of the welfare estimates in this region.

As in Darwin et al. (1995), a number of caveats are also in order with respect to the overall equilibrium effects. First, I have not considered the well-documented, beneficial effects of higher concentrations of atmospheric CO_2 on plant growth and water use. There remains considerable debate about the magnitude of this effect on economic welfare (Darwin, 1997). I also do not consider the negative impacts on crop yields of other gases (particularly ozone, sulfur dioxide, and nitrogen dioxide) released by burning fossil fuels (Wolfe and Erickson, 1993). The latter would tend to offset the former somewhat. Second, procedures for simulating water resources do not include changes in alpine snowpack, assume that water is readily transported to any location within a given region, and neglect negative impacts like flooding, waterlogged soils, and erosion. Third, changes in socioeconomic conditions which might take place by the time climatic changes occur are not considered.

Analyses that includes these and other phenomena will provide a more complete assessment of the potential effects of climatic change on world agriculture in the future. Results from this research also indicate that disaggregation of the Rest-of-World and other regions in FARM’s CGE model may generate additional insights. This is not an easy task. Accurate values for land, labor, capital, and water are scarce, questionable, or subject to erratic movements in many areas. Given the lack of estimates, research on elasticities of transformation of land services is also likely to be a fruitful endeavor. Such research would help delineate and evaluate factors that affect the ease with which land-use changes will be made in response to climatic and other global changes. These factors are likely to include (1) soil or other geological characteristics that might limit agricultural productivity (especially in high latitude areas), (2) production technologies, (3) institutional forces that shape markets for land services, and (4) potential increases in meteorological uncertainty associated with climatic change itself.

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