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WORLD TRADE AS THE ADJUSTMENT MECHANISM OF AGRICULTURE TO CLIMATE CHANGE

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ABSTRACT. This paper evaluates the role of trade as mechanism of economic adjustment to the impacts of climate change on agriculture. The study uses a model of the world economy able to reflect changes in comparative advantage; the model is used to test the hypotheses that trade can assure that, first, satisfying global agricultural demand will not be jeopardized, and, second, general access to food will not decrease. The hypotheses are tested for three alternative scenarios of climate change; under each scenario, regions adjust to the climatic assumptions by changing the land areas devoted to agriculture and the mix of agricultural goods produced, two of the major mechanisms of agricultural adaptation. We find that trade makes it possible to satisfy the world demand for agricultural goods under the changed physical conditions. However, access to food decreases in some regions of the world. Other patterns also emerge that indicate areas of concern in relying on trade as a mechanism for the adjustment of agriculture to likely future changes in climate.

Keywords: climate change, agriculture, international trade, world model.

JEL Classification: Q54, Q17, C61

1. Introduction

The importance of world commodity markets for promoting interregional adjustments in agricultural production in response to climate change was first pointed out by Kane, Reilly and Tobey (1991). Their key finding was that, while climate change may significantly reduce crop yields in some regions, global patterns of production and consumption adjust in such a way that global economic impacts are small.

Other studies (Randhir and Hertel, 2000,Winters *et al*., 1999, Tsigas *et al*., 1996, Darwin *et al.*, 1995, Reilly *et al.*, 1994, and Rosenzweig *et al*., 1993) of the impacts of climate change on agriculture and the role of trade concur that losses of agricultural productivity associated with climate change will not threaten global food sufficiency for the next century or so. It is argued that a well functioning system of trade, responsive to price signals, should help shift commodity production to regions where comparative advantage for agricultural production improves, compensating for potential losses in other regions of the world.

The concept of comparative advantage is regularly invoked as the rationale for viewing international trade as a means for adapting to climate change. The studies cited above, however, are based on mathematical models that do not in fact evaluate changes in comparative advantage. Most adopt the Armington (1969) assumption about traded commodities. This assumption simplifies the determination of trade flows, but at considerable conceptual sacrifice: substitutions among comparable goods produced in different regions are governed by exogenous elasticities rather than being determined endogenously through a direct comparison of changes in cost structures. While the elasticities may yield estimates of commodities produced and traded of plausible magnitudes, they do not reflect comparative costs – the basis for comparative advantage (Duchin, 1994). The arbitrary nature of the Armington assumption has been widely acknowledged, including by analysts who make use of it in the absence of a better alternative (Hertel, 2003, Arndt *et al*., 2001, Winters *et al*., 1999, Darwin *et al*., 1995).

This paper presents a new methodological framework to evaluate trade as a mechanism of adjustment to climate change and uses it to analyze changes in comparative advantage in response to the impacts of climate change. The framework integrates a fully generalized system of trade (for *m* regions, *n* goods and *k* factors) based on comparative advantage in the form of the World Trade Model (WTM) (Duchin, 2005) with the spatial analogues approach to quantifying climatic responses of land resources under alternative climates (Darwin *et al*., 1995). We call this combined framework the World Trade Model with Climate-Sensitive Land, or WTMCL, and use it to test the following hypotheses:

Hypothesis I: The reallocation of agricultural production in response to climate change will allow trade adaptations to function in a way that does not jeopardize meeting global agricultural demand.

Hypothesis II: Changes in world prices of agricultural commodities, in comparison with changes in labor income that result from the reallocation of factor use, do not decrease access to food.

To test these hypotheses, baseline computations calibrated for climatic conditions in the year 1990 are compared with outcomes of three hypothetical scenarios that incorporate alternative assumptions about future climate change obtained with 3 major General

Circulation Models. Our results suggest that trade could make it possible to satisfy world demand for agricultural crops under the changed physical conditions. However, access to food decreases in some regions of the world. Other patterns also emerge that indicate areas of concern in relying on trade as a mechanism for the adjustment of agriculture to climate change.

The next section presents the modeling framework, and Section 3 describes the database and the climate change scenarios used as the basis for evaluating the 2 hypotheses. Section 4 reports the results of the computations, and the final section concludes with a summary and the identification of priorities for further work.

2. Modeling Framework

2.1. THE WORLD TRADE MODEL

Recently, Duchin (2005) introduced a world model that determines trade flows based on comparative advantage in all sectors and regions of the world. Her World Trade Model (WTM) takes the form of a linear program where the values of endogenous variables – output, trade flows, factor scarcity rents and world prices - are endogenously determined on the basis of simultaneous consideration of consumption requirements, technologies, factor endowments and pre-trade factor prices, variables and parameters that are empirically determined and enter the model as exogenous data. The model minimizes factor costs subject to regional consumption demand and factor endowments; the gains from trade arise from the ability of regions and of the world as a whole to sustain given world consumption at minimum factor cost. Scarcity rents and commodity prices in the WTM respond to changes in assumptions, and the direction and magnitude of these responses constitute the solution of the dual linear program. The model was implemented for 10 regions comprising the world economy, 8 sectors and 3 factors of production including land (Duchin, 2005).

For the current study, the WTM was elaborated in several ways. A key aspect of this inquiry is that each region might need to adjust to the climatic assumptions by changing the land areas devoted to agriculture and the mix of crops produced, two of the major mechanisms of agricultural adaptation. An algorithm for determining the low-cost choice of technology and associated prices in a single region, described in Duchin and Lange (1995) was embedded within the WTM framework to allow for the simultaneous selection of cost-minimizing choices of agricultural commodities and area devoted to agricultural production in agro-climatically defined land classes within each individual region, as well as determining the relatively lowest-cost producers in all sectors for the world as a whole.

2.2. THE WORLD TRADE MODEL WITH CLIMATE-SENSITIVE LAND

The World Trade Model with Climate-Sensitive Land (WTMCL) couples the extended WTM with the spatial analogues approach, pioneered by Darwin *et al*. (1995), which is based on the insight that there is a systematic relationship between differences in regional climates and agricultural productivities for specific uses on land of otherwise comparable qualities. Darwin *et al.* represent a region's climate by its mean monthly temperature and mean monthly precipitation. They estimate its length of growing season (LGS) - the longest continuous period in a year that soil temperature and moisture conditions support plant growth - as a function of climate. On this basis, Darwin *et al*. classified global land resources into six classes that are identified in Table I.

Each region is endowed with a distinctive set of potential land-use categories, and different production characteristics are associated with each land-class/land-use pair. Climate change is assumed to alter the regional land-class endowment for each potential land use and, with it, a region's production potential. [1] We adopt the spatial analogues approach rather than simpler alternatives because it treats agricultural land as a climate-sensitive factor of production based on plausible and documented relationships. Availability of suitable land constrains agricultural production possibilities in the WTM, with impacts on a region's comparative advantage. The combined framework allows for the endogenous determination of the optimal international division of labor and world prices associated with exogenous assumptions about changes in climate.

The WTMCL described below has *m* regions, *n* goods, *k* factors, and *s* land classes. It distinguishes three sub-sets of goods: those that are traded but do not use climate-sensitive land (*T*) those that are traded and do use climate-sensitive land (*TL*), and untraded goods (actually services), like electricity in the present implementation (*NT*). The sub-sets *T*, *TL* and *NT* are comprised of *g*, *h* and *q* goods, respectively. The *h* goods of the sub-set *TL* are mapped to the six land-class types (where their production takes place), so a total of (h x s) goods that use climate-sensitive land are distinguished in the set of *n* goods $(n=(hxs)+g+q)$.

The primal WTMCL consists of the following objective function and 5 constraints:

$$\min_{x} \quad \sum_{i=1}^{m} \pi_i' F_i x_i$$

$$s.t. \quad \sum_{i=1}^{m} e_j' \left(I - A_i\right) x_i \geq \sum_{i=1}^{m} e_j' \, y_i \qquad \forall \, j \in T \qquad (1)$$

$$\sum_{i=1}^{m} \sum_{t=1}^{s} e_j' \left(I - A_i\right) x_{i,t} \geq \sum_{i=1}^{m} e_j' y_i \qquad \forall \, j \in TL \qquad (2)$$

$$e_j' \left(I - A_i\right) x_i = e_j' y_i \qquad \forall \, j \in NT; \; i = 1, \ldots, m \qquad (3)$$

$$F_i x_i \leq f_i \qquad i = 1, \ldots, m \qquad (4)$$

$$\sum_{\substack{j \in T \\ j \in NT}} e_z' \, pnt_i \; e_j' (I - A_i) x_i + \sum_{j \in TL} \sum_{t=1}^{s} e_z' \, pnt_i \; e_j' (I - A_i) x_i \leq pnt_i' y_i \qquad i = 1, \ldots, m \qquad (5)$$

$$x \geq 0$$

The dual is:

$$\max_{p_0, v_0, w, r, \alpha} \quad p_0' \left(\sum_{j \in T} \sum_{i=1}^{m} e_j' y_i \right) + v_0' \left(\sum_{j \in TL} \sum_{i=1}^{m} e_j' y_i \right) + \sum_{j \in NT} \sum_{i=1}^{m} w_i e_j' y_i - \sum_{i=1}^{m} r_i' f_i - \sum_{i=1}^{m} \alpha_i p_{nt}{}_i' y_i$$

$$s.t \quad \sum_{j \in T} \left(I - A_i\right)' e_j p_0 + \sum_{j \in TL} \left(I - A_i\right)' e_j v_0 + \sum_{j \in NT} \left(I - A_i\right)' e_j w_i -$$

$$- F_i' r_i - \left(I - A_i\right)' p_{nt}{}_i \leq F_i' \pi_i \qquad i = 1, \ldots, m \qquad (6)$$

$$p_0, v_0, w, r, \alpha \geq 0$$

where

x_i denotes *n* x 1 vector of commodity output in region *i*

p_0 denotes *g* x 1 vector of world commodity prices for the traded commodities that do not use land

v_0 denotes *h* x 1 vector of world commodity prices for the traded commodities that use land

w_i denotes *q* x 1 vector of regional commodity prices for the non-traded commodities in region *i*

r_i denotes *k* x 1 vector of scarcity rents in region *i*

α_i denotes scalar of benefits of trade in region *i*

y_i denotes [*n* – *h* (*s*-1)] x 1 vector of commodity consumption in region *i*

$\pi_{i,}$ denotes *k* x 1 vector of factor prices in region *i*

denotes *k* x 1 vector of factor endowments in region *i*

pnt_i denotes [*n* – *h* (*s*-1)] x 1 vector of pre-trade commodity prices in region *i*

e_j denotes column vector of required length with a 1 in the j^{th} position and 0's everywhere else

e_z denotes [*n* – *h* (*s*-1)] x 1 vector with a 1 in the z^{th} place - corresponding to the *pnt* price of the commodity in the j^{th} position - and 0's everywhere else

A_i denotes *n* x *n* matrix of inter-industry production coefficients in region *i*

$F_{i,}$ denotes *k* x *n* matrix of factor inputs per unit of output in region I

T denotes sub-set of the traded commodities that do not use land

TL denotes sub-set of the traded commodities that use land

NT denotes sub-set of the commodities to be non-traded

t denotes land-class assignment for the elements of the set *TL*

j denotes commodity

i denotes region

The WTMCL satisfies world commodity demand by an allocation of production that minimizes global factor costs at prevailing regional factor prices. Factor endowments need not be fully utilized, and there is no constraint on the regional balance of trade. Each region trades only if its imports are worth more than its exports at pre-trade regional prices.[2] Production constraints are imposed for traded commodities (1 and 2) and non-traded commodities (3), and for regional factor use (4). The selection of land classes for the production of traded agricultural commodities (2) is optimized at the regional as well as global level. The last inequalities in the primal (5) assure that the value of imports exceeds the value of exports at pre-trade prices for each region, assuring that it benefits from trade. The solutions of the primal problem are the vectors of regional output (x_i).

The dual problem consists of an objective function and the price constraints. The solutions are world prices for the 2 sub-sets of traded commodities, p_0 and v_0, and regional prices, w_i, for untraded commodities in region i. The dual program also determines factor scarcity rents, r_i. If factors are not fully utilized, they are valued at their initial prices, π_i; if they are fully utilized, they earn a scarcity rent in addition.[3] World prices consist of payments for intermediate inputs and factor inputs plus scarcity rents and benefit-of-trade rents if applicable. The benefit-of-trade rents, α_i, are payments to regions where the value of exports and imports are just equal at pre-trade prices. The inequality (6) assures that prices are high enough to accommodate costs plus rents (Duchin, 2005).

There is a single world price for each traded commodity. For commodities that use climate-sensitive land, the costs of land naturally depend on the land-class types where production takes place. Thus, the productivities of the land-classes actually utilized in producing regions influence the world price of the commodity through both land prices and scarcity rents. The price slacks in (6) are zero only when the commodity output in a specific region and land-class type is non-zero. Each slack reflects the amount by which a region would have to reduce its production cost to become a producer.[4]

The model was implemented and solved using the GAMS (General Algebraic Modeling System) optimization software.

3. Database

The WTMCL database was constructed for 1990 for 10 regions: North America, the European Community (as it was in 1990), Other Europe, the former Soviet Union, Japan, Eastern Asia (China, Hong Kong, Taiwan and South Korea, with China the dominant economy), Rest of Asia (with India the dominant economy), Latin America, Africa and one region comprising Australia and New Zealand (from now on, Australia). These regions represent a regrouping of the 10 regions of the WTM, with the new regions selected to distinguish areas of agricultural significance, namely Australia and Latin America, while eliminating other distinctions less vital for this study, such as a separate region for Eastern Europe or the oil-rich Middle East.

The industry classification maintains the WTM's 7 non-agricultural sectors (coal, oil, gas, electricity, minerals, manufacturing and services), but agriculture is disaggregated into 3 categories: grains, livestock and rest of agriculture.[5] Factors of production are labor, capital, and land, but land is disaggregated in two major use categories, cropland and pastureland, each of which is subdivided into the 6 land-class types defined by Darwin *et al.* (1995). Each of the agricultural commodities may be produced on any of the agro-climatic land classes; that is, 6 types of grains and rest of agriculture may be distinguished, each mapping to one climatic cropland class type, and six types of livestock, each mapping to a climatic pastureland type. Duchin's WTM database was modified to accommodate the current regional aggregation and to incorporate the additional detail on agricultural commodities, endowments of the alternative land types and associated production technologies (coefficients in A_i and F_i) needed for the analysis.

Regional cropland and pastureland endowments by land-class for 1990 and for the 3 climate scenarios were extracted from the Future Agricultural Resources Model (FARM) database provided by Dr. Roy Darwin of the United States Department of Agriculture (USDA).[6] He also provided estimates for production of major crops and livestock associated with each region and land-class/land-use combination, information needed to estimate the coefficients in F_i (factor requirements per unit of output). These coefficients were computed for each region by dividing the total amount of land in a specific land-class/land-use category by the agricultural commodity quantities produced on that amount of land in the base year of 1990.

Other assumptions were made in building the database. We assumed that land is required only to produce the agricultural commodities while all commodities require capital and labor. While a region's intermediate coefficients, A_i, may also be land-class specific, we assumed for now that they do not differ over land-class types for a given agricultural commodity.

3.1. CLIMATE CHANGE SCENARIOS

The hypotheses described earlier were tested for a Reference Scenario, describing the actual situation in 1990, and 3 Climate Change Scenarios. These 3 scenarios correspond to climatic results obtained for a doubling of atmospheric concentrations of carbon dioxide at the Goddard Institute for Space Studies (GISS), General Fluid Dynamics Laboratory (GFDL), and United Kingdom Meteorological Office (UKMO), respectively. Summary statistics describing the 3 sets of results are shown in Table II. We chose to compare results of all 3 because, while they are in general agreement from a global perspective, the projections of the climate-change models differ for individual geographic regions.

Each climate change scenario affects the suitability of land for agricultural production and is represented in the WTMCL by values of the land endowments (f_i) for a given region. Figure I illustrates the global changes in land-class endowments that are assumed under each of the scenarios. Each scenario entails a redistribution of land-classes from the extreme types to the middle types. Losses of land-classes of type 1 (see Table I for a description) are due to the warming of current boreal, temperate and arctic regions while decreases in type 6 land classes reflect the shortening of the growing season due to diminishing amounts or deteriorating distribution of rainfall. Impacts of the climate change scenarios on the distribution of land-classes are uneven: about 78% of changes occur in land classified as pastureland. This fact has implications for the capacity of the system to compensate for potential losses in productive areas: major gains in land classes of type 3 and 4, especially suitable for grain production, occur mostly in pasturelands while there are actually losses of croplands of the last type.

Although the global changes in land-class types associated with the 3 scenarios move in the same direction, there are differences among them. The GFDL scenario stands out for an increase in croplands of type 5, while the UKMO scenario anticipates the greatest impact of climate change.

The climate-change scenarios also involve assumptions about the potential for the production of agricultural commodities, due to the changes in the distribution of land-classes. Figure II shows that global production potential decreases moderately for grains and rest of agriculture but increases substantially for livestock under all scenarios.

4. Model Computations

We first examine the reallocation of agricultural production under the 3 climate-change scenarios according to computations using the WTMCL. Then we look at the corresponding changes in world agricultural prices (relative to labor income and expenditures in final demand) that result from the reallocation of production.

All scenarios produce feasible solutions of the WTMCL model, meaning that the global capacity to satisfy the 1990 consumption requirements is not jeopardized. However, production is reallocated across land-class types and regions, resulting in different patterns of regional specialization and trade. Figure III highlights the dominant percentage changes in production quantities. Australia expands its livestock production while Other Europe changes its production assignment from grain, which experiences a large decline, to rest of agriculture. The European Community reduces its production share of livestock and, to a lesser degree, of rest of agriculture. Rest of Asia (with India the dominant economy) gains comparative advantage in grain production.

Figure IV compares the pattern of net exports under the Reference Scenario and the 3 climate change scenarios. In most cases the trade patterns under the climate-change scenarios are similar to those of the Reference Scenario, with shifts between exporter and importer status affecting mainly the European regions. Other Europe emerges as a net exporter of rest of agriculture and a net importer of grains under the UKMO and GISS scenarios, while it significantly reduces its exports of grain (while remaining a net exporter) under the GFDL scenario. Rest of Asia increases its exports of grains under all the scenarios.

The European Community becomes a net importer of rest of agriculture at the expense of Latin America, which decreases its exports of that commodity group.

Because of the reallocation of production across regions and land-class types, the total area cultivated as croplands necessary to sustain the 1990 level of consumption increases substantially for all 3 climate change scenarios but decreases slightly for pasturelands (see Table III). Clearly production has had to shift to lands of lower crop productivity.

The direction and magnitude of price responses reflect changes in payments for intermediate inputs and factors of production, including scarcity rents, which result from the geographic shifts in production. World prices increase relative to the Reference Scenario for all 3 agricultural commodities, but mainly for grains and rest of agriculture and mainly for the UKMO climate-change scenario (see Table IV).

Agricultural production shifts mainly to Rest of Asia (essentially India) and, to a lesser extent, Other Europe, Eastern Asia and Australia, all of which experience increases in their labor income (which includes scarcity rents).[7] The remaining regions experience losses, most conspicuously Latin America. The substantial percentage changes in income in Rest of Asia and Latin America is explained by their respective large shares of agricultural labor in the Reference Scenario, which makes them especially susceptible. Job losses in some regions are compensated by gains in others, and global labor income increases modestly for all climate-change scenarios, especially the GFDL scenario. However, global income in the remaining regions decreases under the three climate change scenarios when the big winner and loser (Rest of Asia and Latin America) are not included in the computations (see Table V).

Regions showed significant differences between changes in costs of goods relative to changes in labor income. Table VI shows the ratio of expenditures (in agricultural commodities and in the whole consumption bundle) to income, by region and for the world. The ratio increases for all regions but Rest of Asia, Other Europe and Eastern Asia under the three climate change scenarios. For the world, this ratio becomes larger under the UKMO and GISS climate change scenarios, suggesting that global access to food may decline under these scenarios' assumptions. Expenditure changes in the whole consumption bundle (for all goods) resulted proportionally bigger than increases in income only under the UKMO scenario. However, when Rest of Asia and Latin America (the regions with extreme changes) are excluded from the computations, the ratio increases for agricultural and all commodities under the three climate change scenarios (see Table VI).

5. Conclusions and Discussion

This paper makes use of a new modeling framework to evaluate trade adjustments consistent with changes in comparative advantage in response to the impacts of climate change on agriculture. Changes in land endowments associated with agro-climatic conditions (and related changes in production potential) generate new patterns of regional specialization of production. Regions adjust by changing the mix of agricultural products and the area devoted to agriculture – two of the major mechanisms of adaptation highlighted in the literature. Changes in world prices reflect changes in payments to intermediate inputs and factors of production, including scarcity rents associated with the adjustments. The calculation of scarcity rents on agricultural land is an important contribution of the study.

According to our computations, the reallocation of production and trade flows under the 3 climate change scenarios does not jeopardize the ability to satisfy the global demand for agricultural products. Thus Hypothesis I cannot be rejected.

Our results show a small but consistent increase in world prices of grains, livestock and rest of agriculture due to climate change. Global expenditures on agricultural goods rise relative to global labor income for two of the three climate change scenarios examined (see Figure V). When the regions with extreme gains or losses (Rest of Asia and Latin America) are not included, global income in remaining regions decreases, while expenditures on commodities (agricultural and all goods) increase. Thus, Hypothesis II may need to be rejected.

By contrast with this result, the majority of other studies anticipate that, with the rate of average warming expected over the next century, agricultural prices are likely to continue to follow the downward path observed in the 20th century (Schimmelpfennig *et al*., 1996). Darwin *et al*. (1995) conclude, for example, that world prices of grain, non-grain crops, and livestock will decrease after adjustments to climate change take place. Darwin *et al.* (1995) have regional prices adjust to climate change to restore equilibrium and then compute world price changes as weighted averages of the resulting regional prices. Their results provide an important point of contrast with our results since both studies use the same biophysical assumptions but different economic modeling frameworks. The fact that the model used in this study is the only one to represent trade patterns and prices that reflect comparative advantage through a direct comparison of cost structures makes our results an important counterpoint that provides cause for concern.

Even in this simple framework, factor constraints raise concerns about the long-run sustainability of trade as a mechanism of adjustment and it needs to be emphasized that the scenarios analyzed all assume 1990 demands for agricultural goods. Climate change increases the need for croplands: an expansion of the area of global cropland cultivated would be required to attain the same level of agricultural consumption as in 1990 (see Table III). Future cropland availability and productivity is an issue of major concern in recent years, mostly due to productivity loss related to soil erosion and to the fact that only a small amount of less fertile land remains to meet additional future needs (Schimmelpfennig *et al*., 1996). The requirements for agricultural commodities can be expected to increase substantially in the future due to population growth, compounding the stress due to climate change. Another reason for concern is that results show substantial differences in gains and losses across regions. While the European Community considerably reduces its agricultural production, the uncompensated loss in income is very small. However, Latin America, whose export earnings are mostly from agriculture, is the region that experiences the greatest loss.

Key assumptions made throughout the analysis limit its scope and need to be relaxed in further research. One such assumption is that the levels of exogenous variables and the technical parameters remain as in the Reference Scenario, that is, as in the year 1990. Only the distribution of climatically defined land classes, and associated changes in production potential, change in response to climate change. Thus the scenarios do not reflect the development of new technologies, such as new cultivars and new breeds, neither do they incorporate the increased demands associated with population growth and shifts in diets toward increased consumption of animal products in developing countries. These decisions simplified the scenario development and made it possible to isolate the effect of climate change on agricultural systems and the likely adjustments that can be expected in a global system of trade. In future analysis, implications of the other assumptions also need to be explored.

On the economic side, the scenarios did not represent barriers to trade. For this reason, the solutions exhibited a higher degree of regional specialization than is actually observed. The study did not intend to evaluate effects of trade policies or regulations on the impacts of climate change in a global system of trade. Rather the intention was to determine patterns of comparative advantage based on the fundamentals of the theory, and the gains from trade when exogenous shocks such as climate change alter comparative advantage. A next step could consider constraints imposed on production and trade by alternative trade policies as a mechanism of adjustment. Regional resource constraints other than land, namely fresh water would also reduce the degree of specialization.

The database is ambitious in scope but necessarily crude in its implementation. The focus of this study was on capturing the most significant structural linkages among climate change and global agriculture and evaluating the role that trade may play as an adjustment mechanism. Building a more detailed, well-documented database for this inquiry will be the work of a community of scholars.

Notes

1. This approach is to be distinguished from the “structural” approach, where climate change is introduced by exogenously

determined yield estimations, initiated by Rosenzweig and Parry (1994).

2. Computations were made to determine production and pre-trade prices in the absence of trade; these pre-trade prices are treated as exogenous variables in the WTM and WTMCL.

3. According to the complementary slackness theorem (Luenberger, 1989), scarcity rents are non-zero only when the factor is fully utilized, that is, when there is no slack associated with the corresponding factor constraint in the primal.

4. Alternatively, the slack can be interpreted as the reduction in p_0 that a region experiences from importing the commodity rather than producing it. Reduced costs indicate how much the objective function coefficient of each decision variable would have to improve before the variable could assume a positive value in the optimal solution (Anderson, Sweeney and Williams, 2000).

5. Paddy rice, wheat, and other grains comprise the grain commodity, and rest of agriculture is a residual category.

6. Darwin *et al*. (1995) computed LGS figures from monthly temperature and precipitation data (Lemans and Cramer, 1991)

using the method of Newhall (1980). This information was incorporated into Geographic Information Systems (GIS) software by the World Soil Resources Office of United States Department of Agriculture (USDA) Natural Resources Conservation Services to generate regional distributions of land-class endowments by land-use category

7. Regional labor income is measured as units of labor times the effective price of labor, which includes scarcity rents.

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TABLE I
Main Characteristics of 6 Land-Class Categories

Land Class Type	Length of Growing Season (Days)	Time soil Temperature Above 5°C (Days)	Principal Crops and Cropping Patterns	Sample Regions	
				USA	World
1	0-100	< 125	Sparse forage for rough grazing	Northern Alaska	Greenland.
2	0-100	> 125	Millets, pulses, sparse forage for rough grazing	Mojave Desert	Sahara Desert.
3	101-165	"	Short-season grains; forage: one crop per year	Palouse River Area	Southern Manitoba.
4	166-250	"	Maize: some double-cropping possible. Cotton and rice: double-cropping	Corn Belt	Northern Europe
5	251-300	"	Cotton and rice: double-cropping Common	Tennessee	Zambia
6	301-365	"	Rubber and sugarcane: double-cropping common	Florida, SE Coast	Indonesia

Source: Darwin *et al*., 1995.

TABLE II
Main Characteristics of 3 Climate Change Scenarios

Scenario	Year Calculated	Resolution	Carbon Dioxide	Average Change in Temperature	Average Change in Precipitation
		(Lat. x long).	(ppm)	(°C)	(%)
UKMO	1986	5.00° x 7.5°	640	5.2°	15
GFDL	1988	4.44° x 7.5°	600	4.0°	8
GISS	1982	7.83° x 10.0°	630	4.2°	11

Source: Darwin *et al*., 1995.
Note: Climate change scenarios are the ones generated by the general circulation models of the United Kingdom Meteorological Office (UKMO), the Geophysical Fluid Dynamics Laboratory (GFDL), and the Goddard Institute for Space Studies (GISS).

TABLE III
Use of Cropland and Pastureland under
Alternative Climate Change Scenarios

	Land Use			
	Reference Scenario	UKMO	GFDL	GISS
	(10^6 Hectares)	(% Change)	(% Change)	(% Change)
Croplands	976.96	16.13	14.4	8.94
Pasturelands	433.01	-0.24	-0.24	-0.24

Source: Own computations
Note: Climate change scenarios are the ones generated by the general circulation models of the United Kingdom Meteorological Office (UKMO), the Geophysical Fluid Dynamics Laboratory (GFDL) and the Goddard Institute for Space Studies (GISS).

TABLE IV
Change in World Prices of Agricultural Commodities under Alternative Scenarios (Percent Change from Reference Scenario)

	Climate Change Scenario		
Commodity	UKMO (%)	GFDL (%)	GISS (%)
Grains	1.17	0.65	0.65
Livestock	0.72	0.41	0.41
Rest of Agriculture	1.18	0.65	0.67

Source: Own computations
Note: Climate change scenarios are the ones generated by the general circulation models of the United Kingdom Meteorological Office (UKMO), the Geophysical Fluid Dynamics Laboratory (GFDL) and the Goddard Institute for Space Studies (GISS).

TABLE V
Change in Regional Labor Income under Alternative Scenarios (Percent Change from Reference Scenario)

Region	Climate Change Scenario UKMO (%)	GFDL (%)	GISS (%)
North America	-0.41	-0.35	-0.42
European Community	-0.78	-0.78	-0.78
Other Europe	2.10	1.93	2.14
Former Soviet Union	-0.53	-0.53	-0.53
Japan	0.08	0.04	0.04
Eastern Asia	1.43	0.82	0.82
Rest of Asia	26.86	36.67	24.77
Latin America	-15.14	-15.16	-15.14
Africa	0.00	0.00	0.00
Australia and New Zealand	0.57	0.57	0.57
World	0.61	1.02	0.44
World without Rest of Asia and Latin America	-0.17	-0.23	-0.24

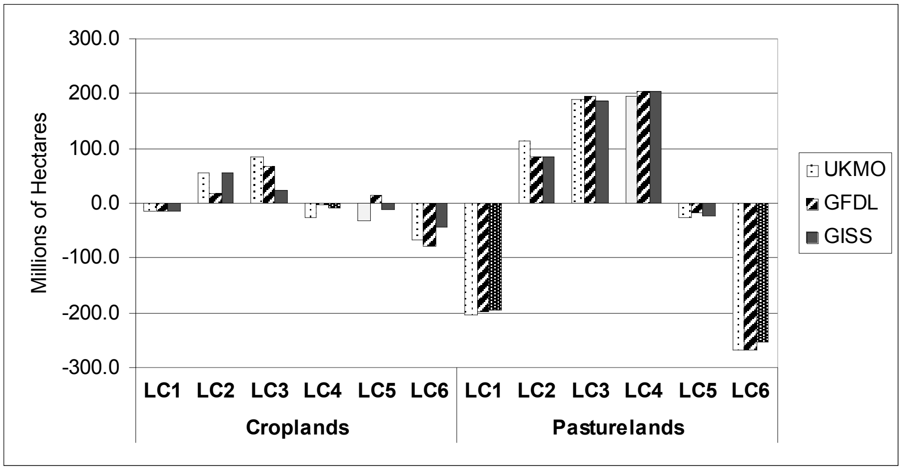
Source: Own computations
Note: Climate change scenarios are the ones generated by the general circulation models of the United Kingdom Meteorological Office (UKMO), the Geophysical Fluid Dynamics Laboratory (GFDL) and the Goddard Institute for Space Studies (GISS).

TABLE VI
Change in Expenditures relative to Labor Income Under Alternative Scenarios (Percent Change from Reference Scenario)

	Agricultural Goods			All Goods		
	Climate Change Scenario			Climate Change Scenario		
Region	UKMO (%)	GFDL (%)	GISS (%)	UKMO (%)	GFDL (%)	GISS (%)
North America	1.6	1.0	1.1	1.7	1.1	1.1
European Community	1.9	1.4	1.4	1.2	0.7	0.7
Other Europe	-0.9	-1.3	-1.5	-1.6	-1.9	-2.1
Former Soviet Union	1.7	1.2	1.2	0.8	0.2	0.2
Japan	1.1	0.6	0.6	0.8	0.1	0.1
Eastern Asia	-0.3	-0.2	-0.2	-0.8	-0.5	-0.5
Rest of Asia	-20.3	-26.4	-19.4	-20.7	-26.6	-19.6
Latin America	19.2	18.6	18.6	18.1	17.8	17.7
Africa	1.1	0.6	0.6	0.3	-0.1	-0.1
Australia and New Zealand	0.6	0.1	0.1	-0.2	-0.8	-0.8
World	0.5	-0.4	0.2	0.2	-0.8	-0.2
World without Rest of Asia and Latin America	1.3	0.9	0.9	1.0	0.5	0.5

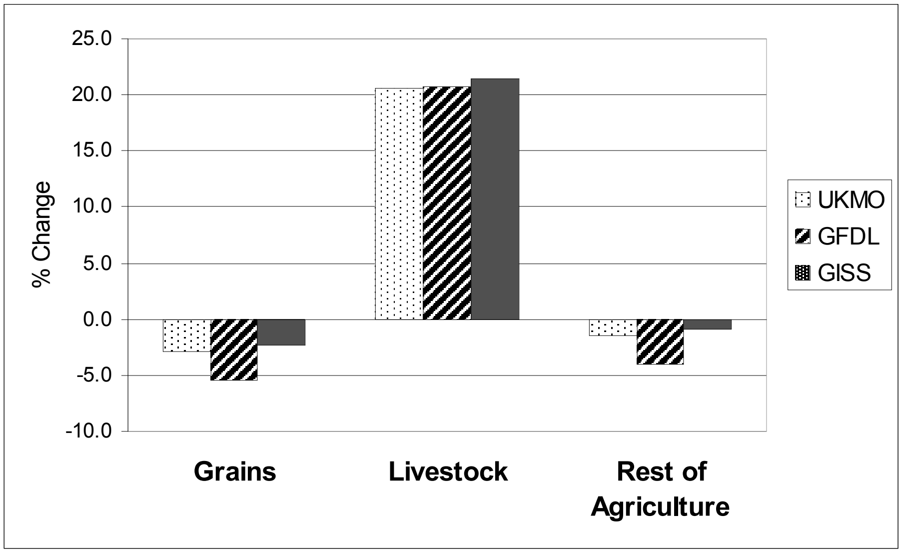
Source: Own computations
Note: Climate change scenarios are the ones generated by the general circulation models of the United Kingdom Meteorological Office (UKMO), the Geophysical Fluid Dynamics Laboratory (GFDL) and the Goddard Institute for Space Studies (GISS).

FIGURE I
Change in Global Endowments of Cropland and Pastureland
by Land-Class Categories under Alternative Scenarios



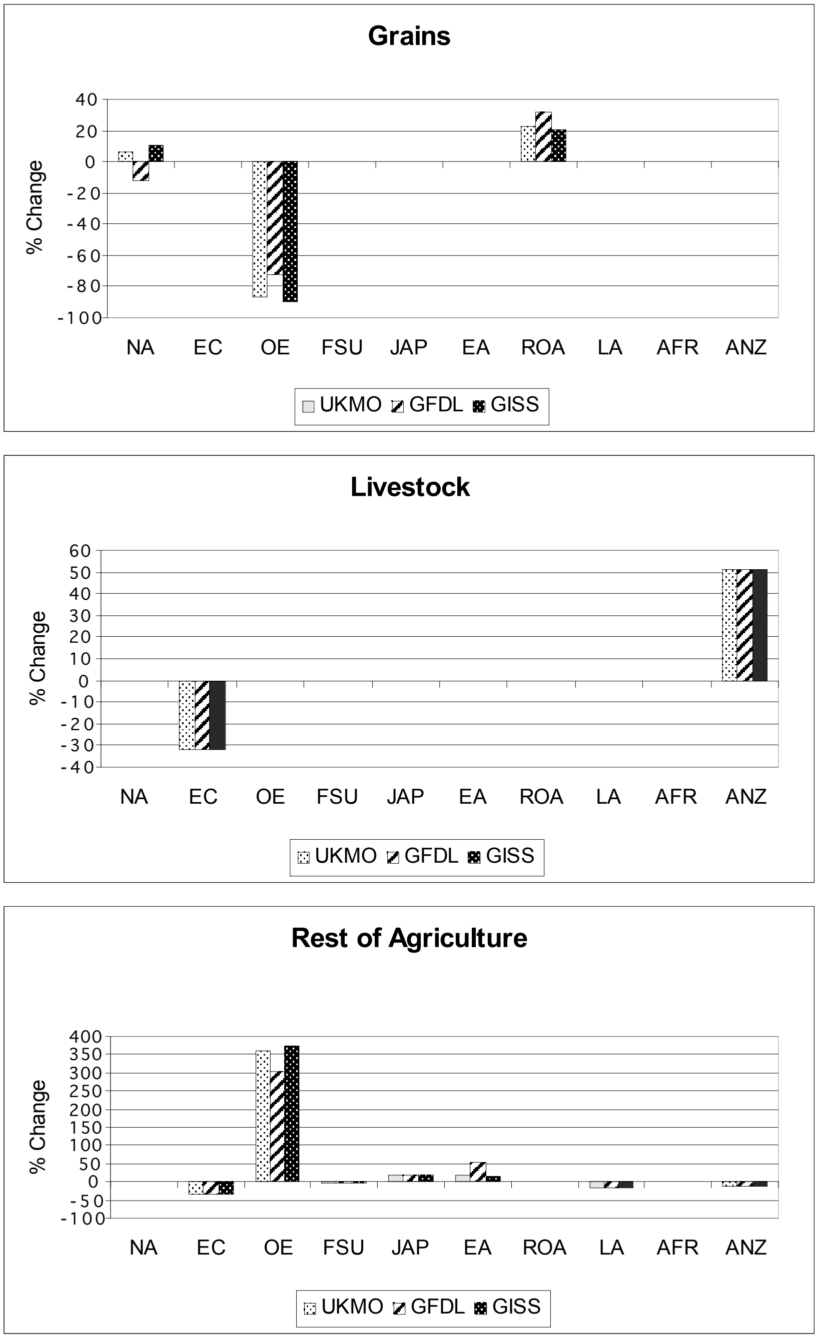
Source: Own computations made from data provided by Roy Darwin (December 12, 2002).
Note: Climate change scenarios are the ones generated by the general circulation models of the United Kingdom Meteorological Office (UKMO), the Geophysical Fluid Dynamics Laboratory (GFDL) and the Goddard Institute for Space Studies (GISS). Land-class categories (LC1-LC6) are described in Table II.

FIGURE II
Change in World Production Potential for Grain, Livestock and Rest of Agriculture under Alternative Climate Change Scenarios



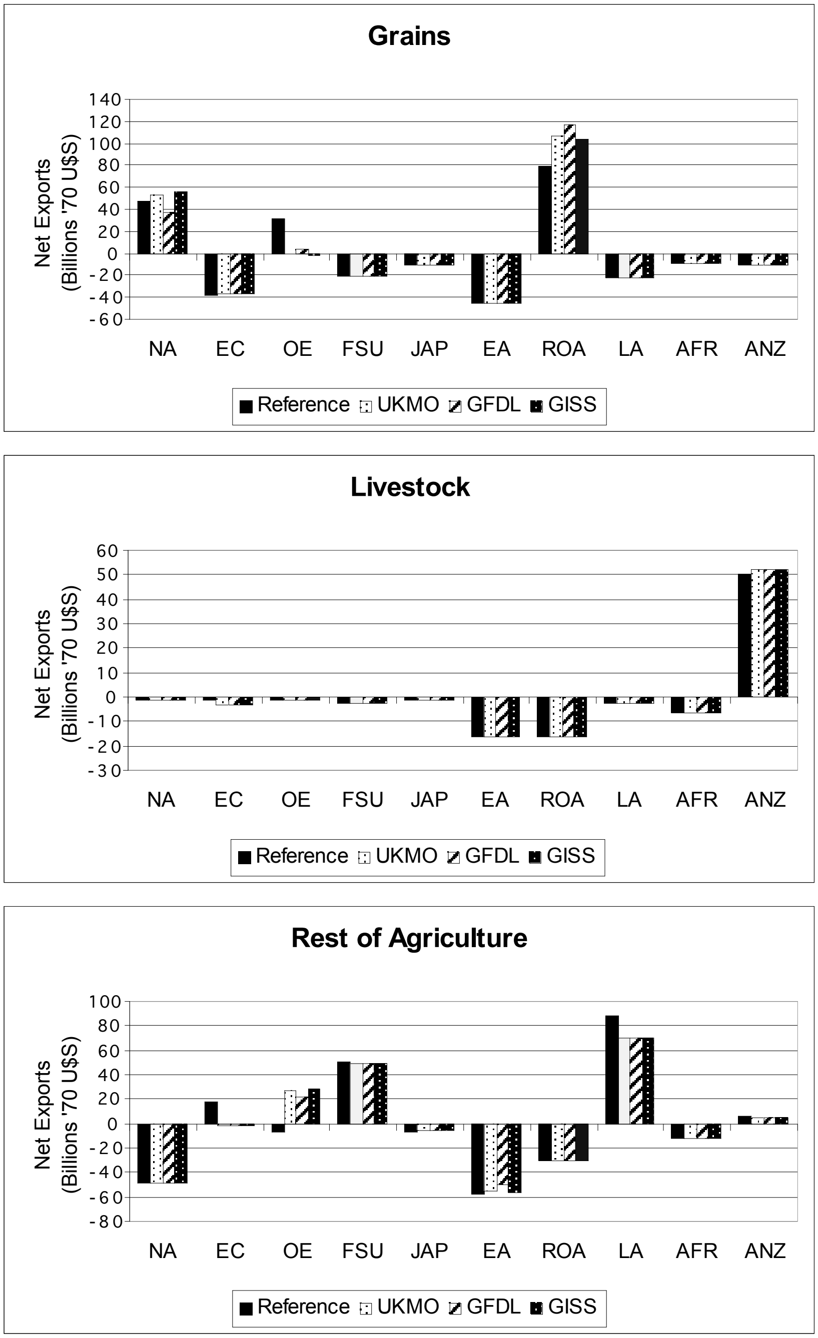
Source: Own computations made from data provided by Roy Darwin.
Note: Climate change scenarios are the ones generated by the general circulation models of the United Kingdom Meteorological Office (UKMO), the Geophysical Fluid Dynamics Laboratory (GFDL) and the Goddard Institute for Space Studies (GISS).

FIGURE III
Change in Production of Grain, Livestock and Rest of Agriculture by Region under Alternative Climate Change Scenarios



Source: Own computations
Note: Climate change scenarios are the ones generated by the general circulation models of the United Kingdom Meteorological Office (UKMO), the Geophysical Fluid Dynamics Laboratory (GFDL) and the Goddard Institute for Space Studies (GISS).

FIGURE IV
Net Exports of Grain, Livestock and Rest of Agriculture
by Region under Alternative Climate Change Scenarios



Source: Own computations made from data provided by Roy Darwin.
Note: Climate change scenarios are the ones generated by the general circulation models of the United Kingdom Meteorological Office (UKMO), the Geophysical Fluid Dynamics Laboratory (GFDL) and the Goddard Institute for Space Studies (GISS). Regions are: North America (NA), European Community (EC), Other Europe (OE), the former Soviet Union (FSU), Japan (JAP), Eastern Asia (EA), Rest of Asia (ROA), Latin America (LA), Africa (AFR), Australia and New Zealand (ANZ).