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FARM: A GLOBAL FRAMEWORK FOR INTEGRATED LAND USE/COVER MODELING

by

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ABSTRACT

The Future Agricultural Resources Model (FARM) was developed by the U.S. Department of Agriculture's Economic Research Service (ERS) to evaluate effects of global changes on agricultural systems. FARM's basic concepts are: 1) climate is the major determinant of land use/cover possibilities, 2) human activity is the major determinate of land use/cover actualities, and 3) globalization of economic activities means that economic changes in one location affect land use/cover in distant locations. These concepts are operationalized by a geographic information system that links climatically defined land and water resources with production possibilities in 12 regions, and an economic model that simulates how changes in one region can affect land and water resources as well as production and consumption of 13 aggregate commodities in eight regions.

Climate is linked with land resources by land classes defined in terms of growing season--the longest continuous period in a year that soil temperature and moisture conditions support plant growth. Each regional land class, in turn, is linked with four land covers--crops, grass, trees, and other--used in commodity production. This enables FARM's economic model to simulate competition for land among crop, livestock, and forestry sectors and interactions of these land-intensive sectors with other sectors. FARM also simulates competition for land among human and other biological communities.

Results from FARM-based analyses include: 1) global climate change and population growth are likely to place additional stress on current agricultural and environmental systems during the 21st century; 2) the net economic effects of global climate change may be positive, however, if humankind is able to take advantage of new agricultural possibilities at high latitudes or in alpine areas, but this adaptation is also associated with fairly extensive changes in land use that are likely to add to environmental stresses; 3) deregulation of trade in agricultural commodities may help to alleviate some of the economic pressure generated by population growth and global climate change, but also may induce land use changes with negative environmental impacts; and 4) setting land aside from economic production to protect natural ecosystems may have relatively low opportunity costs, but global climate change will make it more difficult to implement such programs.

1.0 INTRODUCTION

Projections of population, income growth, and climate during the next century have raised concerns about agricultural and environmental sustainability--our ability to satisfy increased demands for agricultural and environmental goods and services without permanently damaging the world's natural resources. The U.S. Department of Agriculture's Economic Research Service (ERS) has conducted research on these global issues under the U.S. Global Change Research Program since the early 1990's. As part of this effort, ERS developed the Future Agricultural Resources Model (FARM), a modeling framework that uses land use and cover to integrate economic activities with ecological phenomena.

Land use and cover serves as an integrating element for a number of reasons. First, world ecosystem productivity is mainly governed by primary production--the amount of solar energy converted to chemical energy by photosynthesis. For terrestrial ecosystems, the main resource governing primary productivity can be defined in terms of land: that is, for any given level of solar radiation, the principal constraints to terrestrial primary productivity are the area of land available and its soil moisture characteristics. Second, despite the successful substitution of land-based resources with fossil fuel and mineral resources in human economies since the Industrial Revolution began, land remains the primary source of the energy and mass that compose our food and fiber. The agriculture and forestry sectors of human economies, therefore, are still land-intensive. Land also remains a primary factor in all other economic sectors where it mainly provides space. Third, the most important interaction between humans and other biological communities is the competition for land and the services it provides. Modeling this competition is fundamental to conducting integrated analyses of economic activities and ecological phenomena.

2.0 DESCRIPTION OF FARM

FARM explicitly links climatic conditions to land and water resources and to production, trade, and consumption throughout the world. It does this with two components--an environmental framework and an economic framework. The environment is that portion of the world ecosystem that surrounds the human economy. The environmental framework consists of a geographical information system (GIS) that links temperature and precipitation to land and water resources. The resolution of the GIS is 0.5 degrees. The economic framework consists of a computable general equilibrium economic model that links land and water resources to production, trade, and consumption of goods and services throughout the world. The major drivers in the overall framework are climate, population, technology, and consumer preferences. The computable general equilibrium model was developed by modifying the first version of Purdue University's Global Trade Analysis Project (GTAP) model and database.

2.1 Land and Water Resources

Climate is the major determinant of land use/cover possibilities. Monthly temperature and precipitation are used to calculate length of growing season and runoff in a soil moisture and temperature module. Length of growing season is the longest period during the year that soil moisture and temperature are suitable for crop growth. Length of growing season determines the class of a given parcel of land. This approach is also used by the Food and Agriculture Organization (FAO) of the United Nations to define what they call agro-ecological zones. Runoff is approximately precipitation minus evapotranspiration (negatives are converted to zero). Regional runoff is the sum of all runoff from each grid in a region. Regional water supply changes are proportionally linked to regional changes in runoff.

Each region has up to six land classes. Land class (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. LC's 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 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 groundnuts, tobacco, cotton, and rice; double cropping is common. Year-round growing seasons characterize LC 6, which enables it to provide rice, sugar cane, and citrus and tropical fruits.

The LC's also are associated with various ecosystem complexes. Major complexes on LC 1 include polar desert and ice, northern taiga, wooded tundra and heath. Desert, semidesert-tundra, scrub woods, shrub-tree, and grassslands make up most of LC 2. Major complexes on LC 3 are conifer forest and mixed forest. Broadleaf forest is the major complex on LC's 4 and 5. The major complex on LC 6 is tropical forest.

2.2 Land and Water Services

Humans use services provided by land and water resources in economic production. FARM simulates this process by empirically linking each regional land class with four land covers-- crops, grass, trees, and other. The first three covers are used for producing crops, livestock, and forest products, respectively. Other land includes both urban, suburban, and industrial land as well as barren wilderness, wetlands, deserts, etc. Built-up land is used in the production of various manufactured goods and services. Wilderness land is assigned a very small productive role in the provision of services. Hence, each economic sector requires land and all land is taken into account.

This structure enables FARM's economic model to simulate competition for land among crop, livestock, and forestry sectors and interactions of these land-intensive sectors with other sectors. Competition for land among human and other biological communities also is simulated. Grasslands or forests, for example, may be converted to cropland or managed more intensely by increasing animal stocking or timber harvest rates. And, because of our technical preeminence, human activities predominate in this competition and determine land use/cover actualities.

FARM also simulates competition for water among economic sectors. The demand for water originates in three sectors: crops and livestock for irrigation, and services for drinking and other uses. At present, regional supplies of water are perfectly inelastic, that is, water prices do not affect the total amount of water used. Water supplies can increase or decrease, however, in response to climate change and its impact on runoff.

2.3 Other Characteristics

FARM's computable general equilibrium economic model simulates production, consumption, and trade of 13 commodities between eight regions: 1) the United States, 2) Canada, 3) the European Union as of 1990, 4) Japan, 5) other east Asia (China, including Hong Kong and Taiwan, and South Korea), 6 southeast Asia (Indonesia, Malaysia, Philippines, Singapore, and Thailand), 7) Australia and New Zealand, and 8) the rest of the world. The rest-of-world region contains five subregions: 1) the Former Soviet Union, 2) other Europe, 3) other Asia and Oceania, 4) Latin America, and 4) Africa. Information about land use, agricultural and forestry production, and land rents in these subregions is tracked separately and linked with the geographical information system to conduct simple analyses of economic activities in these areas.

Each crop firm in a region may produce three aggregate commodities--wheat, other grains, and non-grains. Each livestock and forest product firm produces one aggregate commodity--livestock and forest products, respectively. Other economic sectors (and commodities) are 1) coal, oil, and gas; 2) other minerals; 3) fish, meat, and milk; 4) other processed foods; 5) clothing, textiles, and footware; 6) other non-metallic manufactures; 7) other manufactures; and 8) services. These commodities are used either within the region of origin or traded to other regions. This globalization of economic activities means that economic changes in one location affect land use and cover in distant locations.

In summary, FARM can be thought of as a set of climate-defined land classes or agro-ecological zones connected to a large global economic model. Within a given region, each land class (up to six) has its own crop producing firm, livestock producing firm, and forest products firm. These firms interact with each other and with other sectors of the economy. International trade ensures that their responses are global. The basic concepts embodied in this structure are: 1) climate is the major determinant of land use/cover possibilities, 2) human activity is the major determinant of land use/cover actualities, and 3) globalization of economic activities means that economic changes in one location affect land use/cover in distant locations.

3.0 RESEARCH RESULTS

FARM has been used to conduct global change research in four areas: global climate change, population growth, agricultural trade deregulation, and global ecosystem protection. Results of this research have been published as an ERS Agricultural Economics Report and in the peer reviewed literature. Additional articles are currently under review. Results presented here will be drawn from all of this material.

3.1 Climate Change

Much of the climate change research in the recent past has understandably focused on agriculture. Most studies have relied on crop growth models to link climate with economic activities. The major shortcomings of this approach are that it is costly to implement globally and it is difficult (if not impossible) to realistically simulate farmer responses to climate change. With FARM, we simply adjust base climate with results from general circulation models (GCMs), recalculate growing season lengths and runoff for each grid, and then determine the aggregate effects on regional land and water resources. Economic adaptation by farmers and other human agents is automatic.

Our climate change research is based on equilibrium results of doubling atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gases estimated from four GCMs: Goddard Institute for Space Studies (GISS), Geophysical Fluid Dynamics Laboratory (GFDL), United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU). Average global mean temperature increases by 2.8 ^{o}C to 5.2 ^{o}C in these scenarios.

3.1.1 *Land Class Endowments*

The global pattern of land class changes is similar for each GCM (Figure 1). The amount of land in LC 1 and LC 6 decreases in all cases, while the amount of land in LC's 2 through 5 generally increases in all cases. Less LC 1 means greater agricultural possibilities at high latitudes or in alpine areas. Less LC 6 means fewer agricultural possibilities in tropical regions. These results also indicate that global climate change is likely to have negative impacts on polar, alpine, and tropical ecosystems. Ecosystems in other areas may expand, but only if they are mobile enough . Populations of plants and animals that are relatively immobile will face some difficulties.

We evaluated the economic impacts of these land class changes with respect to economic conditions in 1990. Two sets of scenarios were evaluated--one with land use fixed at its current locations and another which allowed land use changes to occur. Results from the land-use-fixed scenarios indicate how global climate change might affect the world's current agricultural system. They are also most comparable to results from earlier global climate change studies. Results from the land-use-flexible scenarios show the effects of allowing farmers to take advantage of new agricultural possibilities at high latitudes and in alpine areas. This and the automatic farm-level adaptations simulated in the model are what set our work apart from previous climate change research.

3.1.2 *Economic Welfare*

The effects of global climate change on economic welfare is measured as equivalent variation--the difference, in terms of money expenditure at pre-climate-change prices, between the level of consumer satisfaction under global climate change and the level of consumer satisfaction under no climate change. This is calculated for each region. The population-weighted sum of regional per capita changes in equivalent variation is called total equivalent variation. A decline in total equivalent variation represents a net decline in economic welfare.

Total equivalent variation declines in all land-use-fixed scenarios (Figure 2). The range is from 0.07 to 0.29 percent. The best way to evaluate the size of these changes is to compare them with what are considered to be acceptable economic growth rates, say 2.5 percent per year. The underlying physiological reason for this overall decline is that, on average, less soil moisture is available on current cropland in these climate change scenarios. These results suggests that, even with appropriate on-farm adaptations like switching crops or increasing irrigation, global climate change is likely to impair the world's existing agricultural system. Such decreases in soil moisture are likely to have environmental impacts as well.

Total equivalent variation increases in the land-use-flexible scenarios. The range is from 0.11 to 0.38 percent. The underlying physiological reason for this overall increase is that soil temperature and moisture conditions are more suitable for plant growth in high latitude and alpine regions under global climate change. These results suggest, then, that the net economic effects of global climate change may be positive, if humankind is able to take advantage of these new agricultural possibilities. There is no guarantee, however, that this would happen. Although soil moisture and temperature conditions may be suitable for plant growth at high latitudes or in alpine areas under global climate change, other soil conditions like depth, texture, acidity, or slope, and lighting conditions such as daylength may not be suitable for today's crop varieties.

Values for total equivalent variation in the land-use-flexible scenarios are averages; impacts are more positive in some regions and negative in others (Figure 3). Regional equivalent variation always increases in Canada, the European Union-12, Japan, other east Asia, and the rest-of-world region; it declines in the United States, southeast Asia, and Australia/New Zealand in some instances.

The welfare increases in FARM's rest-of-world region, however, also are likely to mask some major subregional differences. The extent of these differences are indicated by the direct effects of climate change on regional expenditures, i.e., the direct, climate-induced percent change in land income multiplied by the share of total income derived from land in each region. Direct, climate-induced percent changes in land income for the rest-of-world subregions are estimated with FARM's GIS.

Expenditures in the rest-of-world subregions generally decline (Figure 4). The major exception is the former Soviet Union. Economic processes like international trade or exploitation of new agricultural possibilities would tend to reduce and might even offset the welfare losses indicated here. In any event, results in Figures 5 and 6 are consistent with the expectation that agricultural possibilities are likely to decline near the equator, but to increase at high latitudes or in alpine areas under global climate change.

3.1.3 *Land Use Change*

The amount of land changing from one major use/cover to another in the land-use-flexible scenarios ranges from 6.4 to 11.3 percent of all land. And on balance, land is converted to human uses; cropland and pasture increase at the expense of forest land (Figure 5). In addition, production of forest products remains fairly constant on average because of a general increase in timber harvest rates. This means that a greater proportion of the forest resources remaining under global climate change also are likely to be diverted to human uses, leaving fewer forest resources for other organisms.

These results are limited in that economic activity is the only factor in FARM that can generate major land use/cover changes, i.e., replacing a forest ecosystem by a grassland ecosystem or a grassland ecosystem by a desert. Due to soil moisture losses in tropical areas, for example, some forests would be replaced by others while other forests would disappear altogether. FARM implicitly simulates direct climate-induced shifts from one forest ecosystem to another forest ecosystem. FARM does not simulate direct climate-induced changes from forest ecosystems to non-forest ecosystems. Explicit ecosystem modeling will be added in the future.

3.1.4 *Limitations*

There are also a number of general limitations associated with our global climate change results. First, we applied results from equilibrium climate scenarios based solely on a doubling of CO_2 and other greenhouse gases to current economic conditions. The effects of transient scenarios that include the cooling effects of sulfates and other particulates generated during combustion of fossil fuels on possible future economies were not investigated. Second, the direct effects of temperature and increased atmospheric concentrations of CO_2 (a “fertilizer”) and other fossil fuel emissions (mostly pollutants) on agricultural productivity were ignored. Third, sea level rise and changes in riverine hydrology were omitted. Simulations without these limitations, however, are not likely to qualitatively affect the main points presented here.

In summary, global climate change is likely to impair the world’s current agricultural and environmental systems. The net economic effects of global climate change may be positive, however, if humankind is able to take advantage of new agricultural possibilities at high latitudes or in alpine areas. But this adaptation is also associated with fairly extensive changes in land use that are likely to add to environmental stresses.

3.2 World Population Growth and Trade Deregulation

World population is expected to continue to grow during the first half of the 21st century. This growth will cause the demand for goods and services to increase which, in turn, is likely to generate changes in land use/cover. Trade deregulation has well documented economic benefits, but it too may be associated with land use/cover changes. We evaluated the environmental effects of population growth and agricultural trade deregulation on forests in moist tropical regions, that is, forests on LC 6 in FARM’s southeast Asia and rest-of-world regions. For our population growth scenario we imposed expected 5-year regional increases in population, labor, and capital (assumed to equal labor’s growth) on 1990 economic conditions. We simulated deregulation of agricultural trade by imposing a 30 percent reduction in 1990 taxes, subsidies, duties, and tariffs on agricultural commodities in all regions.

Three measures are used to evaluate the environmental effects of population growth on forests: percent changes in forest land, timber harvest rates, and per-hectare timber inventories. Percent changes in timber harvest rates and per-hectare timber inventories are estimated by subtracting percent changes in forest land from percent changes in, respectively, forest output and forest capital. Capital in the forestry sector is primarily timber inventory. Changes in forest land indicate changes in the spatial extent and distribution of forest ecosystems, while changes in timber harvest rates and per-hectare timber inventories imply changes in the health and integrity of existing forest ecosystems. Generally speaking, increases in either timber harvest rates or per-hectare timber inventories (usually in plantations) will have a detrimental impact on natural forest ecosystems. This is because both divert a greater proportion of existing forest resources to human uses, leaving fewer forest resources for other organisms.

In our population growth scenario, forest land in moist tropical area increases by 0.3 percent (Figure 6). This slight increase is associated with a shift of land from the capital- and labor-intensive sectors (manufacturing and services) to the land intensive sectors (crops, livestock, and forestry). Timber harvest rates and per-hectare timber inventories also increase (by 4.9 and 6.4 percent, respectively) in the population scenario. These results suggest that world population growth might slightly stimulate reforestation in moist tropical regions of Latin America, Africa, and Asia. The relatively large increases in timber harvest rates and per-hectare timber inventories, however, indicate that population growth probably has an adverse effect on natural forest ecosystems in the tropics.

Forest land in moist tropical area decreases by 0.2 percent in our trade deregulation scenario. This slight decrease is associated with increases in agricultural production (and land devoted to agriculture) in moist tropical areas because local producers do not have to contend as much with subsidized commodities from and closed commodity markets in OECD countries. To offset the lost forest land, timber harvest rates and per-hectare timber inventories increase by 0.2 and 0.3 percent, respectively. We also found that, as expected, per-capita welfare increases in our trade deregulation scenario.

We have not formally verified these simulated results with an empirical analysis of forestry in the areas considered here. Increases in harvest rates and per-hectare inventories, however, are consistent with widely reported accounts of the removal of old growth forests and the establishment of tree plantations in the area. The slight changes in forest land estimated in this analysis are more difficult to assess. It depends in part on whether removals of old growth forest in the area constitute permanent land use changes. Also, population growth and trade deregulation are only two of the factors that may affect forest land. Other factors not yet evaluated with FARM include the distribution of income across households and the financial investment structure in the area.

In summary, population growth increases the demand for goods and services provided by land-intensive sectors like agriculture and forestry. This is likely to generate negative environmental impacts. Trade deregulation also may have negative environmental impacts, but in this instance they are relatively small and could be easily offset with ecosystem protection policies.

3.3 Ecosystem Protection

The results presented so far indicate how human activities--global climate change, population growth, and trade deregulation--may, through land use/cover changes, destroy the habitats of other living organisms. In this section, results from an evaluation of an extensive program to protect ecosystems are presented. The primary objective of the ecosystem protection program is to prevent the extinction of wild species around the world. The strategy is to set aside land areas that contain the ecosystems in which wild species live. We simulated this program in FARM by removing 10 percent of the world's land from all economic activity. All regions and land classes are subjected to the 10 percent reduction. This is consistent with the position taken by the World Congress on Parks and Protected Areas that 10 percent of all major biomes be protected by the year 2000.

The economic costs of the program are measured by the value of market goods and services (expressed in terms of equivalent variation) forgone by eliminating this land from economic production. A major limitation of this approach is that administrative costs are not taken into account. On the other hand, we have not taken into account that some land already is set aside for ecosystem protection or that ecosystem protection does not necessarily require an absolute ban on economic activity. Also note that we are not concerned with the economic benefits of such an ecosystem protection program in this analysis so they, too, are excluded.

As expected, per-capita economic welfare declines in all regions (Figure 7). The costs are relatively small (0.10 percent or less) in the U.S., Canada, the European Union as of 1990, Japan, and Australia/New Zealand. They are relatively high (greater than 0.25 percent) in other east Asia and southeast Asia. Costs in the rest-of-world region are 0.20 percent. This differentiation reflects the fact that land is a relatively more important source of income in developing regions. This also means that the developing areas in the rest-of-world region--other Asia, Latin America, and Africa--are likely to suffer higher per-capita costs than either the former Soviet Union or other Europe.

The ecosystem protection program also generates some land use/cover changes beyond those prescribed by the program itself (Figure 8). First, although land used for producing crops, livestock, and forest products declines in all regions, the actual percent changes for a given sector may be more less than 10 percent. Second, actual production also generally declines in all regions, but not by as much as land use. This implies that yields or harvest rates of these land-intensive commodities increase. Economic costs would be higher if yields cannot increase as much as indicated here. These results also indicate that ecosystem resources on land that is not set aside may be subject to greater stress than in the absence of an ecosystem protection program.

Finally, global climate change also will render current ecosystem protection programs less effective and make it more difficult to implement new ones. As implied by results in Figure 3, meteorological characteristics of current parks, reservations, and refuges are likely to change but how is highly uncertain. This meteorological uncertainty also increases the difficulty of planning the establishment of new ones. Also, regions that may be negatively affected by global climate change, like southeast Asia, Australia/New Zealand, other Asia, Latin America, and Africa (Figures 3 and 4), would find it more difficult to maintain present or participate in future ecosystem protection programs. These regions are populated with a diverse array of wild species, many of which are already threatened with extinction by economic growth. There simply will be less political incentive to propose that economic growth rates be reduced to protect the environment if they are already reduced somewhat because of global climate change.

In summary, an extensive global ecosystem protection program may have relatively low economic costs when coupled with increased yields in land intensive sectors. Costs differ across regions, however, and developed countries would probably have to compensate developing countries in some way. Global climate change would make it more difficult to implement a global ecosystem protection program.

4.0 SUMMARY AND CONCLUSIONS

ERS has conducted research on global change and agricultural systems since the early 1990's. Much of this research relies on FARM, a modeling framework that uses land use and cover to integrate economic activities with ecological phenomena at a global scale. Despite its advances, the current version of FARM is really a prototype and is relatively crude. A model with greater geographical and sectorial resolution is required for more detailed assessments of potential global change problems and evaluations of mitigating policies. Toward that end, ERS is currently collaborating with the Australian Bureau of Agricultural and Resource Economics to expand our respective capabilities to model the effects of global change. The primary objectives are to develop a new land and water resources database and better methods for conducting dynamic simulations of events in the 21st century.

The land and water resources database will be derived from weather data provided by the University of East Anglia's Climate Research Unit. It consists of 0.5^o gridded monthly time series data from 1901 to 1995. This revised land and water resources database will be compatible with version 4 of the GTAP database of economic activity. It has 45 regions and 50 sectors. The primary tools for linking the land and water resources database with the GTAP database will be the FAO's country level production database, Agrostat, and version 1.2 of the Global Land Cover Characteristics Data Base, with a resolution of 1 km^2. More detailed production data will be used for the U.S., Australia, and other large countries. Dynamic simulations will be improved by extending credible baselines over the entire 21st century and explicitly accounting for investment in and use of water and wood resources. These materials will be made available to the international community.

Despite FARM's current shortcomings, the reasonableness of our results to date indicate that our general approach to modeling relationships between economic and ecological systems is sound. In short, FARM's results provide useful insights about the leading global issues facing today's world. First, global climate change and population growth are likely to place additional stress on current agricultural and environmental systems during the 21st century. Second, the net economic effects of global climate change may be positive, however, if humankind is able to take advantage of new agricultural possibilities at high latitudes or in alpine areas. But this adaptation is also associated with fairly extensive changes in land use that are likely to add to environmental stresses. Third, deregulation of trade in agricultural commodities may help to alleviate some of the economic pressure generated by population growth and global climate change, but also may induce negative environmental impacts in the absence of ecosystem protection programs. Fourth, setting land aside from economic production to protect natural ecosystems may have relatively low economic costs, but global climate change will make it more difficult to implement such programs. A revised FARM framework will continue to add to these insights in the future.

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Figure 8. Ecosystem Protection, Land Use Change, and Production of Land-Intensive Commodities