

Survey of Land Representation in Economic and Biophysical Models

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Abstract. Economic models used for analysis of climate impacts or alternative climate policies are continually evolving to better handle agriculture, forestry, biofuels, and the competition for land among these uses. Ideally, these economic models should be linked to biophysical models that simulate crop or forest growth under varying conditions such as climate, soil, and fertilizer application. However, the biophysical models usually operate on much smaller time steps and geographical areas than the economic models. This paper surveys the way that land is represented in biophysical and economic models commonly used in analysis of climate impacts or climate policy. The survey covers both the representation of land and the economics of land competition in partial and general equilibrium models. A well-known example of a partial-equilibrium model is the Forest and Agricultural Sector Optimization Model (FASOM). An example of a general equilibrium model is the Global Trade Analysis Project (GTAP) model. FASOM covers only the United States, but simulates trade in agricultural products with other countries using external demand relationships. The GTAP model has full bilateral trade between world regions. A biophysical model such as EPIC simulates the way that various crops grow under varying climate, soil, and management practices. EPIC can also provide some indication of the amount of carbon stored in soils and emissions of methane or nitrous oxide. This paper addresses the following questions: How can we link biophysical and economic models? What options are available for the economic models to use information from biophysical models? Are there ways to modify economic models so they capture more of the insights provided by biophysical models? These questions are important as the biophysical models provide information on how managed agriculture responds to climate change, and the tradeoffs between various crop management practices.

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1 Introduction

Economic models used for analysis of climate impacts or alternative climate policies are continually evolving to better handle agriculture, forestry, biofuels, and the competition for land among these uses. These models can be classified on several dimensions: geographical scope, treatment of time, partial- or general-equilibrium, the types of scenarios that can be analyzed, and coverage of greenhouse gas (GHG) mitigation options. Table 1 displays the scenarios of interest for analysis of climate impacts and mitigation policies.

Table 1 Range of scenarios for energy-economy models.

	Without GHG mitigation	With GHG mitigation
Without climate impacts	reference	mitigation
With climate impacts	climate impacts	mitigation + climate impacts

Note: models tend to include greenhouse mitigation or climate impacts, but rarely both.

If the economic model is dynamic, then the reference scenario begins with the present and runs to some future date, say year 2100. A greenhouse gas mitigation scenario introduces a price on carbon dioxide (CO₂) as an incentive to reduce greenhouse gas emissions relative to the reference scenario. A climate impacts scenario provides the economic and land use impacts of a changed climate. Few models can simultaneously calculate the impacts of both mitigation and climate change. Static models can also provide these types of scenarios, imposing climate impacts and greenhouse mitigation policies on the present economy.

There are at least five broad classes of greenhouse gas mitigation options: efficiency in energy demand, efficiency in electricity production, carbon dioxide capture and storage (CCS), fuel switching, and the land-based mitigation options. The land-based, or terrestrial, greenhouse gas mitigation options include storage of carbon in soils, afforestation, forest management, and biofuels. Given the heterogeneity of land in a country, an economic model that considers terrestrial mitigation options or climate impacts must have some way to represent land variability.

Section 2 describes some of the ways that land can be classified. Section 3 describes some of the structures used by economic models to represent land use. However, biophysical models are also needed to describe crop productivity in a changed climate, or any situation where crops migrate to areas where they are not presently grown. This can occur in the reference and mitigation scenarios, as well as in climate scenarios. Section 4 describes some of the biophysical models used to inform economic models. Options for linking economic and biophysical models are discussed in Section 5.

2 Land Classification Frameworks

Due to increasing concern over environmental issues, such as deforestation and climate change, there has been a considerable increase in the development of general and partial equilibrium models of national and multi-national economies that explicitly account for the use of land-based resources across sectors in recent years. These efforts have improved the ability of researchers to consider how shifts in economic forces and policy could affect land use, and in turn how changes in land use affect economies.

A central challenge in building these models is to adequately represent environmental resources in the economy accurately enough to assess the productivity of each unit of land when put to a particular use. The details that are incorporated depend on a number of factors including the focus of the research, data availability, and the scale of the model. This section provides a discussion of how environmental resources have been represented in multi-region and global models.

A better understanding of how approaches differ can be gained by looking at

- data
- spatial scale
- how land rents are calculated
- reallocation of land across sectors

While the first generation of large scale models primarily relied on climate data to differentiate land based resources the increased availability of detailed data for characteristics such as soil, elevation, and slope have made it possible to more fully account for the factors that affect the economic value of land. While any number of approaches are possible, the central tension for the researcher is to develop an approach that is detailed enough to reflect reality while being simple enough to use within an economic model. Before looking at how this issue has been addressed by different projects it is useful to first look at the characteristics of the most commonly used data. Because there are only a few institutions with the resources to collect data at a global scale there is a small set of sources.

Climate: A common source of historical climate data is from the University of East Anglia at 30 arc-minute intervals (0.5° grid cells). This data is often used to define Agro-Ecological Zones.

Soil: The FAO Digital Soil Map (DSMW) is the common source and is at the 5 by 5 minute grid cell level⁴.

Land Use: Spatially aggregated information about area harvested for specific crops at the national or sub-national level often from FAOSTAT.

⁴ <http://www.fao.org/ag/agl/agll/dsmw.HTM>

Land Cover: USGS Eros Data (2000) provides spatially explicit information on land cover according to a set number of land cover types at a resolution of 1 km².⁵

Irrigation: Doll and Seibert (2007) supply estimates of total irrigated land at the 5 by 5 minute grid cell level.

Elevation and Terrain: The USGS GTOPO30 from the USGS Eros Data Center defines elevation at the resolution of 0.5° grid cells. Change in elevation is then used to interpolate the slope or terrain for each cell at the 5 minute grid cell level.

Water: While water is often cited as the biggest data need for global modeling there are some sources available although at a spatially aggregated scale. The World Resources Institute provides information on freshwater withdrawals by country. The Food and Agriculture Organization's (FAO) AQUASTAT is also a common source of data on country level information on water used for crop production.

While this is not a complete list it provides an overview of the typical types of data that are used. How this type of data is combined with additional sources, integrated, and processed to provide information about the economic value of land when put to various uses, varies across different models. One of the great benefits of the development of a community of modelers using different approaches is that it makes it possible to consider how results depend on the approach used. Estimating the economic value of any parcel of land for agriculture is typically a two-step procedure. The first step is to determine whether the environmental conditions meet the minimum requirements for each crop. If minimum requirements are met then the second step is to estimate or measure how productively the crop can be grown.

The International Institute for Applied Systems Analysis (IIASA), in collaboration with the FAO, use an environmental matching procedure defining the climate, soil, and terrain conditions for each crop, and then define Land Utilization Types (LUTs) that integrate biophysical data with information on intensity of farmland management. Management intensity is defined categorically into high, medium, and low for rainfed areas, while irrigated areas are high and medium. Finally, productivity measures for each crop conditional on biophysical, management, and pest and disease characteristics are estimated for each 5' by 5' grid cell using a crop growth model.⁶

The GEO-BENE project has developed an approach called the Homogeneous Response Unit (HRU) that defines a set number of land classes based on relatively stable characteristics including elevation, soil, and terrain for 5' by 5' grid cells (Skalsky, et al.). A set number of categories are defined for each characteristic and the intersection of these categories generates the full list of HRUs. A method is developed to relate these grid cells with weather and country, or sub-country, administrative boundary layers to create homogeneous simulation units that can range from a single 5' by 5' grid cell up to a 30' by 30' grid cell. In a fashion similar to the IIASA/FAO approach, management

⁵ <http://eros.usgs.gov/products/landcover/glcc.php>

⁶ More information about this approach can be found at <http://www.fao.org/ag/agl/agll/gaez/index.htm>.

intensity is defined as a small number of categories reflecting high, medium, and low levels of management.

The GTAP-AEZ approach first differentiates land based on climate data related to the length of the growing season into 6 categories, and further by three climate types. Crops are simplified by defining 8 general crop types (i.e. oil seeds, paddy rice cereals, etc.). GTAP-AEZ incorporates the results from Monfreda, Ramankutty, and Foley (MRF) to allocate crop production spatially to 5' by 5' grid cells. MRF combine satellite and administrative data, and derive harvested area and yield for 175 crops for 5' by 5' grid cells. After the production of each crop is allocated to grid cells it is aggregated in a non-spatial manner according to the AEZ classification of each grid cell.

Other than agriculture, forestry is the other major productive use of land in terms of total area, which makes it an important part of a global land use model. The movement of land between agriculture and forestry has become increasingly important for research on climate change that includes land cover and use in its carbon accounting. As with agriculture, the challenge for researchers is to create a spatially explicit database of forestry resources with non-spatial data at the country or subcountry level. Kindermann et al. (2008) describe an approach for disaggregating FAO country level forestry data to 0.5° grid cells by calculating biomass as a function of net primary productivity and human influence. Another approach is developed for the Global Timber Model (GTM) which is discussed in the next section.

3 Economic Models and Land Use

Economic models used for analysis of alternative climate policies can be classified in various dimensions. Table 2 demonstrates two dimensions: the treatment of time and coverage of markets. Each model in Table 2 is discussed separately, as each represents land in a way different from the others.

Table 2 Model classification

	Partial equilibrium	General equilibrium
Comparative static		FARM, GTAP-AEZ
Dynamic recursive		
Dynamic with limited foresight	AgLU	
Dynamic optimization	FASOM, GTM	

3.1 Global Trade Analysis Program (GTAP)

There is no single GTAP model, but GTAP-AEZ is a version that uses the concept of agro-ecological zones to partition land in each world region. GTAP-AEZ allows land transfer within AEZs, but not between them. There are 18 AEZs within the model (six growing seasons combined with three climate zones: boreal, temperate, and tropics). The

GTAP-AEZ model provides a unique production function for each land use, AEZ, and region combination. This is to identify the difference in the productivity of land of different climate characteristics.

GTAP-AEZ is better suited for analysis of greenhouse gas mitigation options than for climate impacts. In a climate scenario, all of the AEZs would shift and need to be recalculated. Figure 1 provides a description of the land allocation methodology. Each AEZ is first split between forestry and agriculture. Then agricultural land is split between cropland and grazing land. Finally, cropland is split into individual crops. At each nest, an elasticity governs the responsiveness of land use to changes in the rate of return across land uses. Note that elasticities increase (in absolute value) as land is allocated through the nesting structure.

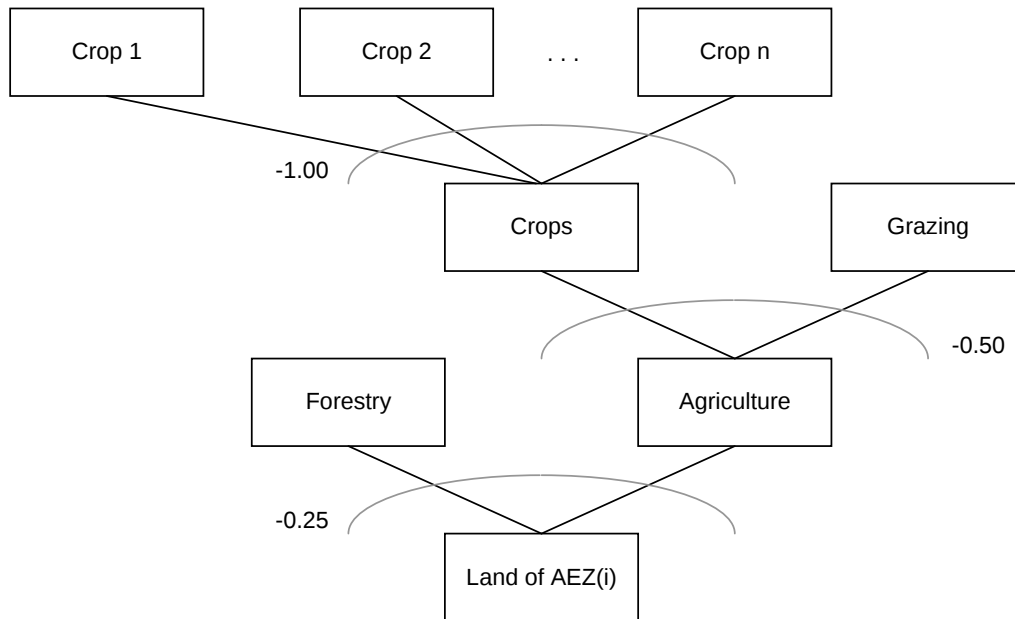


Figure 1 Land allocation in the GTAP-AEZ model.

3.2 Future Agriculture and Resources Model (FARM)

The Future Agricultural Resources Model (FARM) is composed of a geographic information system (GIS) and a computable general equilibrium (CGE) model. The GIS links climate with production possibilities in twelve regions, and the CGE model determines how changes in production possibilities affect production, trade and consumption of 13 commodities (Darwin et al., 1995). FARM's environmental framework links climate variables with six land classes (LCs). Land classes are defined by length of growing season – the length of time during the year that soil temperature and soil moisture conditions are continuously suitable to crop growth. Hence, LCs are similar to AEZ.

The economic framework in the FARM is an aggregation and extension of the Global Trade Analysis Project (GTAP; Hertel, 1997). The FARM divides the world into eight geographic regions and each region has eleven economic sectors that produce 13 tradable commodities. Except for the crop sector, there is a one-to-one correspondence between sectors and commodities. The crop sector is multi-output, producing wheat, other grains and non-grains. FARM's major extensions to GTAP are (1) the inclusion of heterogeneous land endowments, (2) the introduction of water as a primary factor of production in the crops, livestock, and services sector and (3) the modeling of crop production as a multi-output sector (Darwin et al., 1995). These extensions allow accounting for climate-induced changes in the productivity and availability of land and water resources. Water is used for irrigation by the crops and livestock sectors and is used for other purposes by the services sector. Changes in regional water supplies due to climate change are estimated with the revised temperature and precipitation data. Producers' behavior in the FARM is driven by profit maximization assuming competitive markets. Technology in each sector is assumed to be constant returns to scale. Three sectors (crops, livestock, and forestry) are composed of land-class-specific sub-sectors. The FARM does not explicitly consider the land-based carbon sequestration and sink projects, but producers select the most profitable land use under various climate scenarios (so-called economic adaptations), so land use change occurs.

3.3 Agriculture and Land Use (AgLU) component of MiniCAM

The Agriculture and Land Use (AgLU) model was developed to investigate global land use change and the resulting carbon emissions (Sands and Leimbach, 2003; Sands and Edmonds, 2005). The AgLU model is a top-down partial equilibrium economic model with a base year of 1990 and 15-year time steps to 2095.

In this model, the world is divided into 14 regions and production of crops, animal products, forest products, and commercial biomass is simulated within each region. Crops and forest product markets are cleared globally with one world price. Animal product markets are split into 14 regional markets and these markets are cleared when regional supply equals regional demand, adjusted for trade in animal products between regions. Consumer demand for agricultural and forestry products is based on exogenous trends in population, income, and diet constraints with fixed price and income elasticities.

Land use decisions among crops, pasture, and forests are made based on a profit-maximizing principle applied to representative landowners in each region and in each time period. In this model, the productivity within each land use is given a distribution to capture diversity of land quality within the region. Thus, a joint probability distribution is defined over yield in each alternative land use.

The share of land allocated to new forests depends on the profit rate for trees, which depends on the price received for forest products harvested in the future, thus two markets for forest products are brought into the AgLU model. One market is for trees cut today and another market is for trees planted today but harvested in the future. The

current market determines today's price of forest products and the forward market determines a future price of forest products.

Each major land use type is assigned an average carbon density used to calculate a total carbon stock. Carbon emissions from land use change are calculated as the change in carbon stock between time periods, summed across land types. In an effort to simulate a carbon policy, the AgLU model assumes an exogenous carbon price trajectory. The AgLU model provides estimates of carbon emissions from land use change over the next century in response to changing populations, income, and agricultural technologies and evaluates the role of commercial biomass and its impact on land use in a carbon-constrained world.

The land allocation mechanism for each region is shown in Figure 2. Land is first allocated between major land use classes: cropland, managed forest, and unmanaged land. Grassland is handled separately, as the productivity of grassland and rangeland is lower than the other land uses. Cropland is further split into various and biomass. The allocation of land at each nest is determined by relative rates of return to land and an elasticity. Figure 2 has some similarities with Figure 1; the main difference is that Figure 1 is inverted relative to Figure 2.

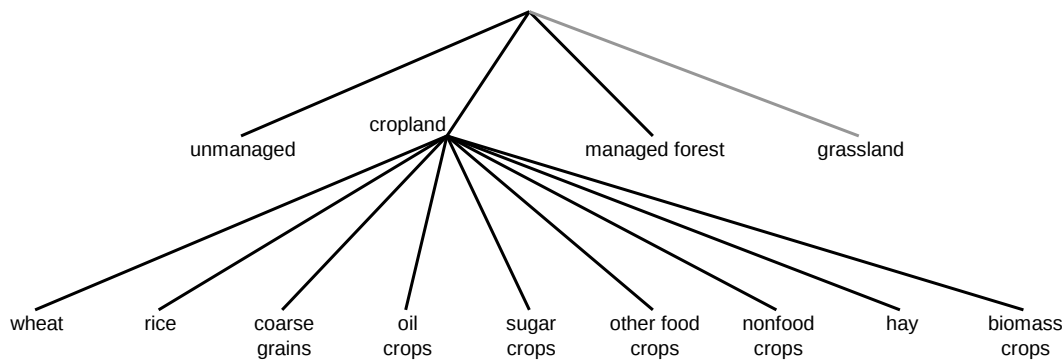


Figure 2 Land allocation in the agriculture and land use component of MiniCAM.

3.4 Forest and Agriculture Sector Optimization Model (FASOM)

The Forest and Agricultural Sector Optimization Model (FASOM) is a dynamic, nonlinear, price-endogenous, mathematical programming model (Adams et al., 1996 and 1999; Alig, Adams and McCarl, 2002). The FASOM is used to evaluate the potential economic impacts of global climate change scenarios on the U.S. forest and agricultural sectors, including impacts on forest carbon inventories and land use and land use change. The model is designed to simulate market behavior with a base year 1990 and decadal time steps to 2090 but policy analysis is limited to results for the 50 years from 1990-2039.

In the FASOM, the equilibrium occurs where prices and production maximizes the present discounted value of aggregated producers' and consumers' surpluses in both

forest and agricultural sectors. The model includes 48 primary agricultural, 45 secondary agricultural commodities, and 8 forest products produced in 11 geographic regions with a single U.S. national demand. Supply curves for agricultural products, sequestered carbon, and stumpage are implicitly generated within the system as the outcome of competitive market forces and market adjustments. The forest sector of the FASOM depicts the use of existing private timberland as well as the reforestation decision on harvesting land.

The land use decision is simulated in FASOM in each period. Landowners decide land use based on the relative profitability of land in its various competing alternative uses over the life-span of the foreseeable choices (for land in either crops or trees). The FASOM simulates land transfer between forest and agricultural sectors. The FASOM is able to account for changes in the quantities of carbon in the major carbon pools in timberland and cropland. The carbon sector in the FASOM is structured such that policy constraints can be imposed on either (or both) the size of the total carbon pool at any given time or the rate of accumulation of carbon from year to year.

These constraints can be imposed by region, owner group, land class, and so forth, consistent with proposed policy instruments. The carbon sector has been designed so that carbon can be valued in the objective function, instead of constrained to meet specific targets.

3.5 Global Timber Model (GTM)

The (Global) Timber Supply Model (TSM) is a dynamic optimization (optimal control) model based on Hotelling's theory (Sohngen, Mendelsohn and Sedjo, 1999, and 2001; Sedjo, Sohngen, and Mendelsohn, 2001). The TSM is used to simulate time profiles for forest biomass, timber harvests, and associated forest carbon in the global forest sector with a base year of 2000 and decadal time steps to 2100. The TSM incorporates 46 timber types in nine geographic regions across the globe.

The TSM maximizes the net present value of global timber market surplus, subject to equations of motion on the quantity of land and stock in different ecosystems and with varying management intensities throughout the world with exogenous global timber demand. Annual net market surplus is consumer surplus from selling timber logs minus the costs of producing timber and holding timberland. The TSM projects decadal harvests for each timber type, the area regenerated, and management intensity. Global timber prices are calculated from the exogenous global timber demand function.

The economic incentives (such as carbon price) for timber production induce economic activities that create more forest stock through planting (reforestation), management to increase forest growth on existing sites, and the establishment of newly planted forests (afforestation). The TSM has two distinct stocks of carbon contained in the forest ecosystem (biomass and soil) and wood products that are created from the harvested wood.

4 Biophysical Models

Ideally, changes in crop yield due to climate change, or changes in the location of crops, should be informed by results from process-based models. Several models are available to estimate changes in yield and input requirements as climate changes or crops move to different locations. Crops can change location either in response to a changed climate or a greenhouse gas mitigation policy that expands the production of biomass as an energy fuel.

4.1 EPIC and APEX⁷

EPIC was originally known as the Erosion Productivity Impact Calculator, but has since been renamed the Environmental Policy Integrated Climate model. EPIC is a field-scale model that runs on a daily time step. Required inputs include daily weather; soil properties; crop management parameters such as crop variety, fertilizer application and tillage practices; and the atmospheric concentration of carbon dioxide. The most important outputs from EPIC are crop yield, emissions of nitrous oxide, and changes in soil carbon.

The Agricultural Policy/Environmental eXtender (APEX) model was developed to extend EPIC from a single field to a farm or small watershed. APEX has the capability to route water, nutrients, and pesticides across a landscape to the watershed outlet. APEX uses the EPIC model to simulate activities on individual farm fields within the farm or watershed.

4.2 CENTURY⁸

The CENTURY model was developed to simulate a wide range of cropping systems and tillage practices to analyze the effects of crop management and climate change on ecosystem productivity. The model simulates long-term dynamics of various ecosystems such as crops, grasslands, savanna, and forests. Further, the model accounts for agricultural management activities such as crop rotation, tillage, fertilizer application, irrigation, grazing, and harvest methods. CENTURY runs on a monthly time step and input variables include: monthly average maximum and minimum air temperature; monthly precipitation; soil texture; initial soil carbon, nitrogen, phosphorus, and sulfur levels; atmospheric and soil nitrogen inputs, and the amount of nitrogen, phosphorous, and sulfur in plants.⁹ A soil organic matter submodel simulates the flows of carbon, nitrogen, phosphorus, and sulfur through inorganic and organic pools in the soil. One advantage of the CENTURY model is that it provides broad geographic coverage of ecosystems.

⁷ The EPIC and APEX web site is <http://epicapex.brc.tamus.edu/>

⁸ The CENTURY home page is at <http://www.nrel.colostate.edu/projects/century/>

⁹ DAYCENT is a version of CENTURY that runs on daily time steps.

4.3 BIOME3

BIOME3 is an equilibrium terrestrial biosphere model suitable for simulating the steady state of unmanaged ecosystems. Model inputs include latitude, soil quality, atmospheric carbon dioxide concentration and monthly climate data on a 0.5° grid. BIOME3 simulates competition between plant functional types (PFTs) within each grid cell and reports the net primary production (NPP) of the dominant PFT. The model has been used for integrated analysis of the impacts of climate change and carbon dioxide concentration on unmanaged ecosystems in the United States (Izaurre et al., 2005).

4.4 SWAT (Soil and Water Assessment Tool)¹⁰

Much of the world's food is grown with irrigation water. This water often has competing uses, such as electricity generation and preserving stream flows for fish and recreation. Even without climate change, demands on water will increase with a growing population. A hydrology model can be particularly useful in scenarios that include climate change, with changing precipitation patterns, melting of glaciers, and early melting of mountain snowpack. Models for the integrated assessment of climate change have little or no representation of water, even though the availability of water is a constraint on the expansion of energy crops.

SWAT is a hydrology model that operates on a daily time step at the scale of a watershed. Inputs to the SWAT model for a given watershed include weather, soil properties, topography, vegetation, and land management. One of the key outputs of SWAT is total runoff for the watershed, based primarily on maintaining water balance in the water basin.

5 Options for Linking Biophysical and Economic Models

Static economic models simulate one year of activity. If the economic model is dynamic, time steps could be at one-year, five-year, or ten-year intervals, with stock variables (such as capital stocks) or parameters (such as population) updated each time step. When using output from biophysical models to inform economic models, one must consider time scale, geographical scale, and geographical scope (single-country or global).

Climate inputs to biophysical models such as EPIC or CENTURY can be daily or monthly, and a historical record of weather data, for 30 or more years, can be used to establish a reference scenario. Key output variables, such as crop yield, are available at annual time scale and are easily matched to the annual time scale of economic models. A common strategy is to run the biophysical models separately and use their output variables as exogenous inputs to economic models. However, as models begin to link water supply with agricultural production, a monthly time step may be needed for the hydrology and agricultural supply components.

¹⁰ The SWAT home page is at <http://www.brc.tamus.edu/swat/>

Global economic models used for analysis of climate policy generally partition countries into 10 to 20 regions: a region could be a large country, say the U.S. or China, or a group of countries, say Western Europe. Within each region, there must be some way to represent the heterogeneity of the land resource. This usually means partitioning each region into land classes. One strategy is to collect data at the grid cell level and aggregate to a larger land unit for economic modeling. The larger unit could be watersheds, political boundaries such as states within the US, or a collection of grid cells based on land characteristics.

It may not be possible to collect comparable data for all countries in the world, or one may be interested in the results for one country more than others. One strategy, such as used in FASOM, is to model a single-country with the rest of the world represented by export demand curves. Even with a global model, it may be useful to provide more land disaggregation in some regions than others, resulting in an asymmetric model. This is possible if international trade is represented in the same way for all world regions.

Forests present another challenge for global economic models. Due to the time difference between planting and harvest, forestry is inherently intertemporal. However, global economic models tend to be either static or dynamic recursive. Either the representation of forests must be simplified, such as a steady-state, or the dynamics of the economic model needs some form of foresight.

Many of the biophysical models are complex and require many simulations to build an input data set for an economic model. Another strategy is to construct a simplified version of a biophysical model. We can think of this as a compact structural model, that runs interactively inside an economic model. The IMAGE project uses simplified representations of biophysical processes that can be run quickly and interactively (Leemans and van den Born, 1994).

6 Research Agenda

Models are constructed to address specific questions. In the case of climate change, some of the relevant questions are:

1. What greenhouse gas mitigation options are available to stabilize greenhouse gas concentrations?
2. What types of biofuel pathways are available?
3. How might land use change over time in a reference scenario, a greenhouse gas mitigation scenario, and a climate impacts scenario?
4. How can we calculate carbon emissions from land use change?

5. Are there ways to modify economic models so they capture more of the insights provided by biophysical models?

To handle questions related to land use, the economic modeling community has considered several ways to partition land within countries. There is still a need to refine and compare these methods, especially if water constraints are to be included.

There are many options for biofuel pathways within an economic model. Sources of biomass include crop residue, switchgrass, sugar cane, and short-rotation trees. Biofuel feedstocks can be burned directly to raise steam for electricity generation, gasified, or converted to liquid fuels. Biofuel-based electricity generation can also be combined with geological storage of carbon dioxide. Ideally, an economic model would be able to simulate all of these biofuel pathways and compare them on the basis of cost.

Global economic models used for analysis of climate policy should also be able to address leakage that occurs through international trade. For example, if a country has a policy to increase the production of biofuels, what land use changes are induced within that country and in other countries? What is the net impact on global greenhouse gas emissions? This is another important area of research for global economic models.

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