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Agriculture, Land Use, and Commercial Biomass Energy

A Preliminary Integrated Analysis of the Potential Role of Biomass Energy for Reducing Future Greenhouse Related Emissions

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June 1996

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest National Laboratory
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(a) Exxon Research

ABSTRACT

Population, income, energy, agriculture, and land-use are intimately tied together in a set of relationships which govern land-use change greenhouse related emissions, food security, and energy production, use, and greenhouse related emissions. To date these issues have generally been handled separately. For many purposes this approach is serviceable. But recent interest in reducing fossil fuel carbon emissions have focused on the development of renewable energy technologies. One of the more promising technologies is biomass energy. But to provide large scale contributions to the energy system requires that biomass energy become part of the modern agricultural sector. This has potential implications for other agricultural production and for rates of land-use change emissions. In this paper we explore some of the interactions between commercial biomass energy production, land-use change emissions, and total anthropogenic carbon emissions. We find that the introduction of commercial biomass energy tends to accelerate the rate of intrusion into unmanaged ecosystems, and to accelerate land-use change emissions, but that the overall effect on total anthropogenic carbon emissions to reduce them.

SUMMARY

In this paper we have considered commercial biomass energy in the context of overall agriculture and land-use change. We have described a model of energy, agriculture, and land-use and employed that model to examine the implications of commercial biomass energy or both energy sector and land-use change carbon emissions. In general we find that the introduction of biomass energy has a negative effect on the extent of unmanaged ecosystems. Commercial biomass introduces a major new land use which raises land rental rates, and provides an incentive to bring more land into production, increasing the rate of incursion into unmanaged ecosystems. But while the emergence of a commercial biomass industry may increase land-use change emissions, the overall effect is strongly to reduce total anthropogenic carbon emissions. Further, the higher the rate of commercial biomass energy productivity, the lower net emissions. Higher commercial biomass energy productivity, while leading to higher land-use change emissions, has a far stronger effect on fossil fuel carbon emissions. Highly productive and inexpensive commercial biomass energy technologies appear to have a substantial depressing effect on total anthropogenic carbon emissions, though their introduction raises the rental rate on land, providing incentives for greater rates of deforestation than in the reference case.

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While we are grateful for the financial support for the conduct of our research provided EPRI and DOE, the views expressed in this paper are solely those of the authors and were formed and expressed without reference to positions taken by these institutions. The views of the authors are not intended to either reflect or imply positions of either EPRI or DOE.

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INTRODUCTION

Advanced energy technologies, and particularly modern commercial biomass, have been identified as potentially important components of low greenhouse emissions trajectories by many researchers including, for example, Williams 1994a; Edmonds et al. 1994; Lashof and Tirpak 1989; Goldemberg et al. 1987. One of the acknowledged weaknesses of previous analyses is that they do not take into account the interplay between the energy sector, the agricultural sector, and land-use change.

In almost all forward looking energy assessments, commercial biomass energy plays a role in providing the world's energy (IPCC 1992, 1995). The expansion of biomass energy will inevitably create a new demand for land, which in turn will have implications for the full array of other land uses, competing with conventional crops, grazing lands, and commercial forests. This in turn can potentially drive up prices for food and fiber, lowering the living standards of the world's poor, and put added pressure on unmanaged ecosystems, accelerating the rate of deforestation and frustrating the very emissions carbon emissions reductions that the introduction of these technologies were intended to affect. The introduction of commercial biomass may also have the effect of mitigating the trend toward urbanization and maintaining land rental rates in the face of agricultural modernization.

The cost and overall effectiveness of achieving low greenhouse-related emissions trajectories through the use of commercial biomass cultivation cannot be assessed without applying of an analytical tool capable of jointly assessing both energy and land use. To assess these issues, we have created a new capability, the Agriculture-Land-Use (AGLU) model within the MiniCAM model (Edmonds et al. 1995) to explicitly model agriculture and land use, endogenously determine land-use change emissions, and integrate land use with the terrestrial carbon cycle. We refer to this new version of MiniCAM as MiniCAM 2.0. We employ this new capability to explore the use of biomass as an element of a strategy of anthropogenic carbon emissions. We place particular emphasis on the interplay of technological change in crop and livestock productivity, the boundary between managed and unmanaged ecosystems, the terrestrial carbon cycle, and atmospheric CO_2 concentrations. The analysis presented here is intended to demonstrate the potential usefulness of this tool and to provide some initial insights with regard to commercial biomass interactions with land use.

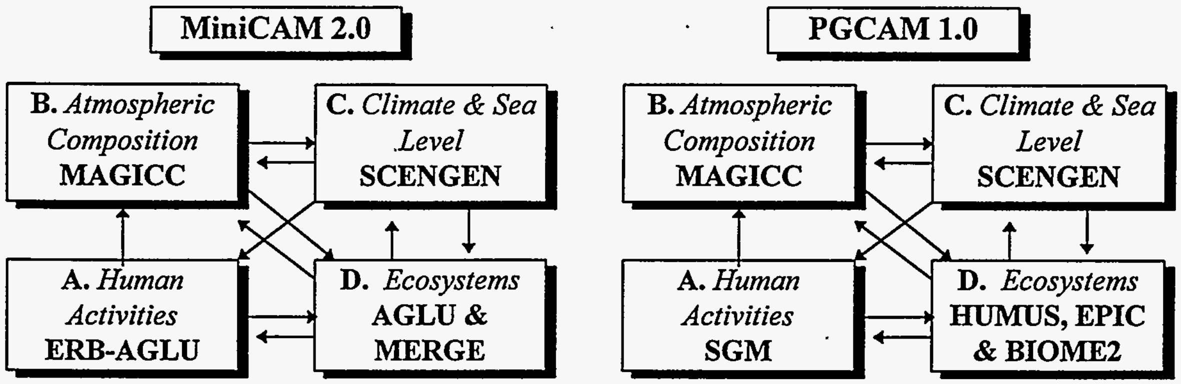
In the section that follows, we describe MiniCAM 2.0. We then proceed to construct a reference case which mirrors the forecast of the IPCC Case IS92a (Leggett et al. 1992). Finally, we consider the implication of alternative assumptions about the productivity of commercial biomass crops.

MiniCAM 2.0

The MiniCAM 2.0 is a set of simple models within the Pacific Northwest National Laboratory (PNNL) Global Change Assessment Model (GCAM) system. The GCAM system comprises tools drawn from relevant research areas to form an integrated assessment model (IAM). GCAM is unique in that it contains two parallel, but interconnected, model development programs. The first is a reduced form representation of global change, the MiniCAM. The second is a process-oriented representation of global change, the PGCAM. These two modeling systems are shown in Figure 1.

Each modeling system is thought of as containing four major components: (A) Human Activities, (B) Atmospheric Composition, (C) Climate and Sea Level, and (D) Ecosystems. The MiniCAM uses the Edmonds-Reilly-Barns (ERB) model (Edmonds and Reilly 1985; Reilly et al. 1987; Edmonds and Barns 1992) to describe the energy system within Human Activities and the new Agriculture-Land-Use module (AGLU) to represent land-intensive human activities. The composition of the atmosphere, global mean surface temperature, and sea level is described by the MAGICC model (Wigley and Raper 1992, 1987). Regional climate change is described by the SCENGEN model.[1] Economic damage is described by the MERGE model (Manne, Mendelsohn, and Richels 1993).

FIGURE 1: Modules and Models Used In The GCAM



The MiniCAM is benchmarked to 1975, employs a 15-year time step, and disaggregates the world into eleven geopolitical regions:

1. United States
2. Canada
3. Western Europe
4. Japan
5. Australia & New Zealand
6. Eastern Europe and the Former Soviet Union
7. China and centrally planned Asia
8. Middle East
9. Africa
10. Latin America
11. Other South and East Asia

The MiniCAM tracks emissions of the following greenhouse-related gases (GRGs): CO_2, CO, CH_4, VOCs, N_2O, NO_x, and SO_2, in addition to chlorofluorocarbons (CFCs) and their substitutes.

THE AGRICULTURE-LAND-USE MODULE (AGLU) IN MiniCAM 2.0

Land use is divided into two types: Managed and Less Managed. Managed lands are employed for one of five purposes: (1) crop production, (2) livestock production, (3) forestry, (4) modern biomass production, and (5) urban uses. Less managed lands are disaggregated into eight categories: (1) wetlands, (2) tundra, (3) grasslands, (4) boreal forests, (5) temperate forests, (6) tropical forests, (7) deserts, and (8) other. Less managed lands can be either available for human activities, or "parked" (unavailable for use to raise crops, livestock, or commercial forestry). This structure is shown in Figure 2.

The AGLU is a dynamic market equilibrium model. The principal components of the AGLU are shown in Figure 3. The model employs information on supplies and demands for crops, livestock, and forest products to develop estimates of market clearing prices. The model is highly non-linear. Model outputs are the allocation of land resources to alternative applications, production and consumption of crops, livestock, biomass, and forest products, and emissions from land-use change.[2] The remainder of this section provides a detailed description of the AGLU model.

---

[1] Information given by T.M.L. Wigley, personal communication, 1994.

[2] While not incorporated in AGLU version 1.0, later versions of the model will incorporate the impacts of climate change, CO_2 fertilization, commercial fertilization, and water availability and use.

Final Demands: The demand for crops, livestock, forest products, and traditional biomass fuels, in region j, $Q_{di,j}$, is given by the following equation:

$$Q_{d,i,j,t} = A_{d,i,j}\ f(y_{j,t})\ P_{d,i,j,t}^{rpijt}\ N_{j,t} \qquad (1)$$

where A is a constant term, N_j is the population of region j, $P_{d,i,j,t}$ is the price to consumers of product i (i=crops, livestock, and forest products) in region j in period t, rpijt is the price elasticity of demand for product i in region j in period t, where

$$f(y_{j,t}) = B_{d,i}\ y_{j,t} / (y_{j,t}\ C_{d,i} + C_{d,i}^{2}) \qquad \text{i=crops, livestock}$$
$$f(y_{j,t}) = y_{j,t}^{ryijt} \qquad \text{i=forest products, traditional biomass}$$

where ryijt is the income elasticity of demand for product i in region j in period t, y_j is per capita income in region j, and $B_{d,i}$, $C_{d,i}$ are coefficients governing asymptotic consumption and the rate of convergence. Because livestock are fed using both rangeland and feedcrops, there is a demand for crops which originates as a derived demand for crops. That is a fractions $S_{i,j,t}$ of cattle feed which is provided by feed grains. Income elasticities of demand for crops and livestock are assumed to decline with income until they reach zero.

The demand for modern biomass is given by the ERB component of the MiniCAM.

Supply of Rapidly Maturing Products: For products which mature within one time step, 15 years, the supply of products is given by a set of relationships. Land allocation in the model is driven by the expected rate of return on a parcel of land, the rental rate on a unit of land. The average expected rate of return on a parcel of land producing product i, in region j, $R_{i,j}$, is given by the following equation:

$$R_{i,j,t} = P_{s,i,j,t}\ q_{i,j,t} - h_{i,j,t} \qquad (2)$$

where $q_{i,j}$ is the average potential productivity of product i in region j, and $h_{i,j}$ is the average cost of per unit land of production. Average potential productivity in turn depends on a variety of factors, including technology in use to produce product i, in region j, in period t, $k_{i,j,t}$, climate in region j in period t, $m_{j,t}$, the concentration of atmospheric CO_2, $CO_{2\,j,t}$, and the application of fertilizer, $Z_{i,j,t}$,

$$q_{i,j,t} = A_{s,i,j}\, k_{i,j,t}\, m_{j,t}\, CO_{2\,j,t}\, Z_{i,j,t} \qquad (3)$$

where $A_{s,i,j}$ is a calibration constant. Each of the major factors affecting productivity is maintained as an index normalized to 1.0 in the base year. In MiniCAM version 2.0, values for variables other than technology are maintained at their initial values. Technological change is entered as an exogenous assumption for each period.

Note that the form changes slightly for the production of livestock. Livestock are treated as if they were simple transformers of pasture and grazing land productivity. Thus, in the case of livestock two terms are added to the above equation,

$$q_{i,j,t} = A_{s,i,j}\, k_{i,j,t}\, m_{j,t}\, CO_{2\,j,t}\, Z_{i,j,t}\, B_{i,j,t} / (1 - S_{i,j,t}) \quad \text{i=livestock} \qquad (3')$$

where $B_{i,j,t}$ is the transformation coefficient for livestock, when i is livestock, and $S_{i,j,t}$ is the share of livestock nutrition provided by feedgrains,

For the production of modern biomass, crop residues are assumed to be available up to a maximum of V per unit land, beginning at a cost of $V_{min,j,t}$ and rising linearly to $V_{max,i,t}$ at full harvest of residues.

The production of fish is determined by the following relationships:

$$F_t = F_{t-1}\ (1 + l) - Q_t \qquad (4)$$

where F_t is the stock of fish in period t, l is the rate of growth of fisheries, and Q_t is annual production. The harvest of fish is given by

$$F_t = F_t P_{i,j,t} / (P_{s,i,j,t} + a) \quad (5)$$

where a is a parameter determining the rate of rise of cost with respect to stock depletion.

Managed Forests: Managed forests generally require more than one period in which to mature. It is therefore important to develop a multi-period, vintaged model for forests. For each vintage, v, of forests, there is a different growth rate per unit land. Tree growth typically follows an "S" shaped function. Thus, the growth of a vintage of trees is given by

$$q_{i,j,t} = A_{s,i,j}\, k_{i,j,t}\, m_{j,t}\, CO_{2,j,t}\, Z_{i,j,t}\, g_{v,i,j,t} \qquad i=\text{forests} \quad (3")$$

where $g_{v,i,j,t}$ is the growth factor appropriate to trees of vintage v.

The Allocation of Land: Land is partitioned into two fundamental categories: managed and less managed lands. Less managed lands in turn are composed of those lands which could potentially become managed for production of goods and services, and those which are "parked," i.e., withheld from human development. Within managed lands there is a similar dichotomy between lands which are utilized intensively for the support of human habitat and those which are used extensively for the production of crops, livestock, forests, and biomass.

Managed lands are allocated between habitat and extensive uses hierarchically. That is, demands for habitat are assumed always to be satisfied first. The demand for lands for habitat is approximated by

$$L_{h,j,t} = N_{j,t}\ [a_j\, y_{j,t}^{ryh,j,t}\, (N_{j,t}/L_j)^{rh,i}] \quad (5)$$

where $L_{h,j,t}$ denotes land area allocated to use h in region j in period t, L_j is total land area in region j, $ry_{h,j,t}$ is the income elasticity of demand for land, and $r_{h,i}$ is the density elasticity.

Land is allocated among competing uses on the basis of a Logit function. The fraction of managed land in region j, in period t, allocated to the production of output i, $s_{i,j,t}$, is given by

$$s_{i,j,k,t} = a_{i,j,k} R_{i,j,t}^{rjk} / (S_i\, a_{i,j,k} R_{i,j,t}^{rjk}) \quad (6)$$

where $a_{i,j,k}$ is a calibration constant for product i, in region j, using productive factor k, where k is land; and rjk is the Logit distribution parameter.

The distribution of land between managed and less managed depends on the expected rental rate on a unit of land. The expected rental rate on a unit of land in the managed system, excluding land for habitat ($L_{h,j,t}$), is computed as

$$R_{j,t} = (S_i\, a_{i,j,k} R_{i,j,t}^{rjk})^{(1/rjk)}. \quad (7)$$

As the rental rate rises, the share of land in the managed system rises. The total extent of less managed land, $L_{u,j,t}$, is the sum of parked land, plus other less managed lands and computed as

$$L_{u,j,t} = L_{u,parked,j,t} + (bL\, L_{u,j,t}) / (L - (1-b) L_{u,j,t-1}). \quad (8)$$

where $L_{u,parked,j,t}$ is parked less managed lands, $L=_t (L_j - L_{h,j,t} - L_{u,parked,j,t})$, and $b=(R_{i,t}/R_{i,t-1})$.

Production of product i in region j in period t, $Q_{i,j,t}$, is thus computed as

$$Q_{s,i,j,k,t} = s_{i,j,k,t} (L_j - L_{h,j,t} - L_{u,j,t})\, q_{i,j,t} \quad (9)$$

where $L_{u,j,t}$ is land in less managed systems.

The supply of forest products depends on the harvest rate. The harvest rate in turn depends on the expected rate of interest rate, INT, the price of the forest products, the cost of harvest, $h_{i,j,t}$, and the growth function $g_{j,t}(v)$. Harvest occurs for all vintages V^* and greater where V^* satisfies

$$INT = P_{s,i,j,t}\, g'_{j,t}(V^*)\, [P_{s,i,j,t}\, g_{j,t}(V^*) - h_{i,j,t}]^{-1}. \qquad (10)$$

International Prices and Trade: All products can be traded, though the model employs an algorithm which allows biomass to only trade if it is transformed into a liquid or gas. For crops, livestock, and forest products, international markets are assumed to clear. An international price is computed for each product, P_j. Regional prices differ from the international price by taxes, tariffs, subsidies, and transport costs. The price paid by regional consumers is given by

$$P_{d,i,j,t} = (P_{i,t}\, tf_{1,i,j,t} + tr_{i,t})\, tx_{1,i,j,t} + tx_{2,i,j,t}. \qquad (11)$$

where $tf_{1,i,j,t}$ is the tariff rate, $tr_{i,t}$ is the transport cost, and $tx_{1,i,j,t}$ and $tx_{2,i,j,t}$ are multiplicative and additive taxes respectively. Similarly the price received is given by

$$P_{s,i,j,t} = (P_{i,t}\, tf_{1,i,j,t} + tr_{i,t})\, sub_{1,i,j,t} + sub_{2,i,j,t}. \qquad (12)$$

where $sub_{1,i,j,t}$ and $sub_{2,i,j,t}$ are multiplicative and additive subsidies respectively.

Markets are said to clear when

$$0 = S_j\, Q_{d,i,j,t}(P_{i,t}) - Q_{s,i,j,t}(P_{i,t}). \qquad (13)$$

We utilize the same non-linear search algorithm employed by the ERB (Edmonds and Reilly, 1985) to solve this market system.

Land-Use Emissions in MiniCAM 2.0: Three greenhouse-related emissions (GREs) are tracked in the MiniCAM 2.0: terrestrial carbon, agricultural methane from rice cultivation and livestock, and nitrous oxide from nitrogen fertilizers. In MiniCAM version 2.0 terrestrial carbon fluxes are handled simply. Carbon stored in the terrestrial biosphere can be computed as

$$C_t = S_i\, c_i\, L_{i,j,t}\,. \qquad (14)$$

where C_t is the stock of terrestrial carbon at the end of period t, the index i extends over all land use categories, and c_i is the average carbon intensity of that land use. Anthropogenic carbon emissions are computed as the difference in terrestrial stocks of carbon between two periods at an annual rate plus fluxes from biomass products.

$$DC_t = C_t - C_{t-1}. \qquad (15)$$

Other transfers among carbon reservoirs, such as those associated with soils, dead matter, charcoal, and CO_2 fertilization are handled within the terrestrial carbon cycle component of MAGICC.[3]

Emissions from CH_4 are the sum of land-use emissions from ruminant livestock and rice paddies. Emissions are related to activity levels as follows:

[3] In MiniCAM 1.0 the supply of biomass energy was developed from a supply schedule which did not take non-energy land-uses explicitly into account. Emissions from land-use change were provided as exogenous assumptions, taken from the IPCC IS92 scenario set (IPCC 1992; Leggett et al. 1992). MiniCAM 2.0 differs from MiniCAM 1.0 in that the former employs a markets for crops, livestock, and forest products and traditional biomass fuels in addition to providing supplies of biomass to the ERB. Emissions from land-use change can also be computed directly from the regionally estimated stocks of biomass.

$$E_{i,j,t} = e_{i,j,t}\, s_{i,j,t}\, Q_{i,j,t}, \qquad (16)$$

where i denotes livestock or crops, $s_{i,j,t}$ is the share of livestock which are ruminant (i=livestock) or the share of crops which are paddy rice (i=crops), and $e_{i,j,t}$ is a time-dependent, region-specific emission rate.

The treatment of nitrous oxide emission from the application of fertilizer are handled similarly, using

$$E_{i,j,t} = e_{i,j,t}\, Z_{i,j,t}\, L_{i,j,t}, \qquad (17)$$

where i=crops.

Model Parameters in the AGLU: The AGLU model is calibrated to reproduce 1975. This is accomplished by specifying the constant coefficients for equations governing the production and consumption of products to match control values. Control data for crops, and livestock were taken from Roningen et al. (1991) and Sullivan et al. (1992). Forest demand and production are taken from the United Nations Food and Agricultural Organization (FAO) (1993,1995). Price and income elasticity estimates are adopted from the SWOPSIM model (Roningen et al. 1991; Sullivan et al. 1992), while the asymptotic consumption limits for final crop and livestock consumption are developed from econometric estimation of parameters from cross-sectional data drawn from United Nations FAO (1993,1995) for the year 1975. Period-specific growth factors for regional forests are taken from Avery and Burkhart (1983). The effects of commercial fertilizer applications are not specified separately in this exercise. Thus, all productivity gains are accounted in the exogenous productivity parameter. Similarly, neither climate nor CO_2 fertilization effects are addressed in this exercise but will be the focus of subsequent research efforts.

Land-use patterns for 1975 for each region and land coverage classification seen in Figure 2 are based on merged data sets of land use and the areal extent of biomes (an ecological classification of land coverage). These alternative descriptions of land coverage are merged into the classifications shown in Figure 2. To merge the data sets, we first require the land areas of more managed (including urban) lands to match land use data. Next, we split land that is classified by biome into more managed and a less managed (including parked) parts.[4] For example, the large areas of pastures in land-use assessments come from some combination of biomes that include grasslands, forests and other lands. Finally, the more detailed differentiations of biomes that exist in the data sets are lumped into the types shown in Figure 2.

Land use for crops and pasture land (livestock) are taken directly (i.e., without alteration) from the FAO yearbook (1993). We then modify this classification to include biomass crops grown in Brazil by removing this from the FAO value of Brazil's crops. In addition we add an estimate of land use for settlements, i.e., habitat or urban, such as that given for the United States by Meyer (1995).

The FAO classification is not consistent (Houghton 1994) with ecosystem-based classifications (Olson et al. 1983). To address this inconsistency we first group Olson et al.'s (1983) 57 classifications into our classifications which include both use classifications (e.g., cropland and pastures) and ecosystem classifications (e.g., grasslands and temperate forests). The grouped ecosystem classifications underestimate, with respect to our land allocations outlined above, the amount of land that is settled, cropland or pastures, and do not differentiate between parked land or land used for forestry. The land allocations of the grouped ecosystem classifications are then modified by shifting land classified by likely ecosystem types (e.g., savannas) to land uses (e.g., pasture lands) in order to make one consistent classification. In this way we retain a good approximation of both the carbon content and the productivity of the land cover with our land assignments.

Carbon sources and sinks for changes in land coverage depend primarily the carbon stored above ground (tonC/ha) which contribute to emissions if the land is cleared, and the Net Ecosystem Productivity (tonC/ha/yr) which determines in part the rate at which a disturbed ecosystem can build up stored carbon. Values for each of our land

[4] In this analysis we do not assign any lands to the parked category. All lands treated as if they are potentially available for use. This simplifying assumption overestimates the extent of land that is available, as some lands are withdrawn as parks and are unavailable for any commercial activities.

classifications are taken from Schlesinger (1991). The bulk of carbon stored in above-ground biomass is in tree covered lands; therefore, the largest net sources or sinks of land use carbon come from the clearing or growth of forests.

AGRICULTURE, FORESTRY, AND LAND USE IN THE TWENTY-FIRST CENTURY

Land use has changed greatly over the past century. These changes have come about in part at least as a response to the complex of interactions between population, income, and agricultural productivity. The degree to which agricultural productivity trends can persist into the next century depend on a number of factors including agricultural technology development and diffusion, soil quality and quality change, and physical constraints on land and resources.

Assumptions: To explore interactions between agriculture, forestry, and land-use and their implications for climate, we apply a set of assumptions to the energy and agriculture modules. For comparison purposes, we have chosen to use assumptions that are consistent with the IS92a developed by the IPCC in Leggett et al. (1992). Principal assumptions governing the energy and economic sectors are given in Table 1.

Table 1: Key Assumptions: Energy and Economy

PARAMETER	Reference Case
Exogenous End-Use Energy Intensity Improvement Rate	OECD: 0.5%/yr EEFSU: 2.5%/yr CHINA: 2.2%/yr ROW: 0.3%/yr
Fossil Fuel Resources Oil Gas Coal Uranium	 18,011 EJ 17,451 EJ 271,000 EJ 14,423 EJ (extend w. breeder option)
Conventional Fossil Fuel Power Plant Efficiency	33% in 1990 66% by 2050
Global Population (year 2100)	$11,312 \times 10^6$
Global GNP Growth	2.3%/year

The variety of assumptions that goven the results of the AGLU module are given in Table 2. Substantial regional productivity growth rate differences exist. In our prospective work, we constrain each region's productivity and productivity growth rate to equal its experience, but change these rate over time to asymptotically approach the common growth rate. In developing regions where there is a greater difference between current practice and best available practice than in developed regions, productivity growth rates are increased. In this analysis we take no account of climate feedback and CO_2 fertilization effects. These phenomena are presently addressed in an aggregate manner in the MAGICC carbon cycle model. The development of a more sophisticated treatment of agriculture-climate-CO_2 interactions in which the terrestrial carbon cycle is fully endogenized within the ALM is a prime near-term model development objective.

Table 2: Key Assumptions: Agriculture and Land-Use

PARAMETER	Reference Case
Rate of Exogenous Productivity Improvement	
Crops	1.5%/yr
Livestock	1.5%/yr
Managed Forests	0.5%/yr
Fuelwood	0.5%/yr
Initial Price Elasticities	
Crops	-0.2
Livestock	-0.2
Managed Forests	-0.4
Fuelwood	-0.4
Initial Income Elasticities	
Managed Forests	0.2
Fuelwood	-0.2
Asymptotic Demands	
Crops	0.95 Mg/cap/yr
Livestock	0.21 Mg/cap/yr
Biomass Productivity	
1990	6 Mg/ha/yr
2095	10 Mg/ha/yr

Energy in the Reference Case: Since we have chosen a set of energy input assumptions which are consistent with the IPCC IS92a it is not surprising that the reference case differs little from those reported by IPCC IS92a. The reference case portrays a world increasingly dominated by the production and consumption of coal beginning in the middle of the next century. Fossil fuel carbon emissions grow to approximately 20 PgC/yr by the year 2100. Primary energy production increases from approximately 350 EJ/yr in 1990 to more than 1400 EJ/yr in the year 2095. This is despite the fact that commercial biomass provides an increasingly important share of the energy in the reference case.[5] The biomass energy industry comes into existence after the year 2005 in the IS92a case as it does in our reference case. By the year 2095, modern commercial biomass more than 180 EJ/yr of the world's energy needs.

Agriculture and Land Use in the Reference Case: In the reference case, agricultural production grows over time, driven by increasing population, income per capita, and crop productivity. This is shown in Figure 4. Crop and livestock production more than triple between 1975 and 2095. The increase in crops is a function of increasing population demand and a shift in consumption patterns toward livestock, which in turn creates a derived demand for crops which serve as animal feed. Direct per capita consumption of crop products remains relatively steady until growing slightly. This is because per capita direct consumption of corps is either saturated or relatively close to saturation in most parts of the world. Thus, the increasing per capita income that occurs in the reference case leads to increased demands for livestock, but increases in per capita demand for crops only in those parts of the world which are currently poor. In contrast, per capita crop production more than doubles over the course of the next century because of increasing capita consumption of livestock products, Figure 5. The demand for forest products also increases, but less rapidly than population. Use of traditional biomass fuelwood grows slowly to the year 2035 where it peaks. Its use per capita declines steadily. The declining growth rate of traditional biomass energy use is a

[5] Recall that biomass energy consumption is treated as if it produced no net carbon in as much as all of the carbon released on combustion was removed from the atmosphere during plant growth. As a consequence, we adjust land-use emissions to reflect this treatment, and report only net changes to the stock of standing biomass resulting from the use of commercial biomass.

result of increasing population size being tempered by higher per capita income levels which lower traditional biomass per capita consumption.

International trade in crops continues to grow over time. Three regions are net importers of crops over the entire course of the next century: the Middle East, Latin America, and Other South and East Asia. The availability of arable land explains the increasing dependence of the Middle East on imports. The cases of Latin America and Other South and East Asia are different. Land is not a constraint in these regions. Commercial biomass energy production is a relatively secondary consumer of land, though land used in commercial biomass grows to the point that in 2095 almost as much land is in biomass (740x 10^6 ha) as in crop production (960 x 10^6 ha). But this is as much owing to the shift away from land in crops as it is to the increased shift toward land in commercial biomass. The decline in the allocation of land to cropping results from a combination of the static demand for end-use crops coupled with rising crop productivity. Commercial biomass remains a relatively minor land use in comparison to either pasture or forests.

Modern commercial biomass begins to become significant between 2005 and 2020. By the year 2050 70 EJ/yr are being produced, and by the year 2095 commercial biomass production is more than 125 EJ/yr, Figure 6. The largest regional producers are Africa and EEFSU, which together account for half of global production with Africa alone accounting for more than 30 percent.

Biomass trade grows after the year 2005, though most commercial biomass production is used locally. Less than 10 percent of global energy use is provided by biomass imports. The greatest flow of commercial biomass trade is between EEFSU and Other South and East Asia, Figure 7.

During the course of the next century, the general shape of land use evolves. The extent of land applied to crops and livestock increases somewhat. In addition, the creation of a new commercial biomass agricultural activity requires land. Taken together, these features imply continued pressure on forests and unmanaged ecosystems, though the pressure declines over time, Figure 8. By the end of the next century the extent of unmanaged lands declines by about one-fifth. Land-use emissions peak by the year 2035, and decline so that by the year 2095, emissions are negative. Interestingly, the extent of land diverted to commercial biomass energy supply remains relatively small, despite the fact that approximately ten percent of global energy is being supplied by this source by the middle of the next century. Commercial biomass energy production takes up approximately six percent of total land area by the end of the next century. This is, however, only slightly more land than is apportioned to corps, whose productivity growth and saturation in end use lead to declining land apportionments over the course of the next century.

The implication of these tendencies for net land-use carbon emissions is shown in Figure 9. MiniCAM 2.0 computes land-use carbon emission. Emissions from land-use change are 0.7 PgC/yr in 1990, though this figure reflects a 15-year average rate. It is at the low end of the range of potential land-use change emissions reported by IPCC (1996), whose central value is 1.3 PgC/yr for the decade 1980 to 1990. Several observations are worth making. First, the scale of land-use change carbon emissions relative to fossil fuel carbon emissions is relatively smaller and declines with time. Second, land-use change carbon emissions are relatively stable in the near term, rise with the introduction of large-scale commercial biomass energy, then decline. By the end of the century, land-use change emissions have become negative. That is, more carbon is being sequestered in the form of forest regrowth than is being removed from the system through harvests. This tendency contrasts with the profile of net land-use change carbon emissions developed in the IS92a. There land-use change emissions decline steadily from the present.

Net land-use change carbon emissions remain steady through the first quarter of the next century. Rising per capita incomes expand production of livestock, which in turn implies increased conversions to pasture land. The area under cultivation for managed forests decreases during this period, adding to the release of carbon from unmanaged ecosystems. The introduction of biomass at the end of the first quarter of the next century leads to an increase in the rate of land-use change emissions. These peak by the middle of the next century and begin to decline thereafter as population growth rates recede, agricultural technological change drops only slightly from an average of 2.0%/yr to 1.5%/yr, and food demands tend to saturate. By the end of the century global deforestation actually turns negative.

A variety of other researchers have examined the issue of net emissions from land-use change. These include Leggett et al. (1992), Lashof and Tirpak (1989), Alcamo (1994), Matsuoka, Kainuma, and Morita (1993), and Houghton (1991). Figure 10 compares the reference scenario generated in this study to 13 other scenarios found in the literature. Most of the scenarios have a similar character to them. Emissions remain above 0.5 PgC/yr, but below 2.0 PgC/yr. Scenarios such as those of Leggett et al. (1992), IS92 a,b,c,e,f are all of this character, as are Lashof and Tirpak (1989) rapidly changing world (RCW), Alcamo (1994), "Conventional Wisdom," and the Matsuoka, Kainuma, and Morita (1993) "AIM" scenario. A few scenarios show somewhat higher and lower emissions, for example Lashof and Tirpak (1989), Slowly Changing World (SCW), which was higher, and Leggett et al. (1992), IS92d which was lower. Of the IPCC scenarios, only the sensitivity case which explored a high deforestation scenario, IS92 S1, gave significantly higher emissions than our reference case. In contrast, earlier studies such as Houghton (1991) and Lashof and Tirpak (1989) show generally higher emissions in all cases except those in which reforestation is actively pursued as a policy intervention. We also note that Houghton (1991) uses a substantially higher initial level of land-use change emissions.

TECHNOLOGICAL CHANGE IN AGRICULTURE, FORESTRY AND BIOMASS AND LAND USE

Numerous studies of energy systems, including Nordhaus and Yohe (1983), Edmonds et al. (1986), Manne and Richels (1993) and de Vries et al. (1994), have established the importance of technological change assumptions in determining reference fossil fuel carbon emissions. This raises the question of the sensitivity of land-use change emissions to future rates of technological change. To address this issue, reference case assumptions regarding commercial biomass energy, crops, pastures and forest productivities have been systematically changed. Six new cases, defined in Table 3, are compared to the reference case.

Table 3: Sensitivity Case Descriptions

Case	Case Name	Biomass Productivity, Year 1990	Rate of Commercial Biomass & Forestry Productivity Growth	Rate of Crop & Livestock Productivity Growth
1	**Reference Case**	**6 T/ha/yr**	**0.5%/yr**	**1.5%/yr**
2	Rapid Productivity Growth	6 T/ha/yr	*1.0%/yr*	*2.0%/yr*
3	No Productivity Growth	6 T/ha/yr	*0%/yr*	*0%/yr*
4	No Biomass Productivity Growth	6 T/ha/yr	*0%/yr*	1.5%/yr
5	No Crop Producivity Growth	6 T/ha/yr	0.5%/yr	*0%/yr*
6	High Biomass Productivity	*12 T/ha/yr*	0.5%/yr	1.5%/yr
7	Very High Biomass Productivity	*20T/ha/yr*	*0.5%/yr*	1.5%/yr

Cases 2 and 3 explore the implication of higher and lower rates of productivity growth in crops, livestock, forestry, and biomass energy production respectively. Cases 4 and 5 are designed to examine the implications of stagnation in productivity growth for either forest and commercial biomass energy productivity, or crop and livestock. The final two cases, 6 and 7, explore the implication of high biomass energy productivity alone.

In assessing the effects of land-use productivity change it is important to take into account the links between the energy and land-use sectors. Biomass energy is an attractive alternative to fossil fuels as an energy carrier. Because the carbon released to the atmosphere upon its oxidation was taken from the atmosphere, biomass can be produced in a way that results in no net emissions to the atmosphere. In fact, because biomass absorbs CO_2 from the atmosphere during its growth phase, a growing biomass energy system in which relied on cultivated biomass, as opposed to deforestation, would actually be increasing the stock of terrestrial carbon. However, this effect is minor for modern commercial biomass crops. As noted in the introduction, a number of authors have shown that if biomass can be made sufficiently productive it can become a dominant energy form in the next century.

But the potential of commercial biomass energy to perform these functions depends on a number of interactions with other land-use activities. Specifically we are interested in the degree to which commercial biomass energy competes with crops, livestock, and forestry for land resources, as well as the degree to which the increasing demand for lands results in either direct or indirect pressures to bring less managed ecosystems into the managed category.

A great deal of attention has been focused on the productivity of biomass as a determinant of biomass penetration of the energy market. But much less attention has been placed on interaction of agricultural and livestock productivity with biomass. Work by Williams (1994b) indicates that competition among competing land uses need not slow the penetration of biomass energy. But this work does not take land-use market effects into account. That is, commercial biomass energy provides a new demand for land. The introduction of this land use will increase the demand for land, raise the land rental rate, and exert increasing pressure on deforestation. This effect can be seen in the reference case. The introduction of commercial biomass energy coincides with the an increase in land-use change emissions in the reference case after the year 2005.

Figure 11 shows the implications of all seven cases for land-use change emissions and Figure 12 shows the implication for total anthropogenic carbon emissions. The envelope of the highest and lowest scenarios are provided for comparison, as are the two IPCC IS92 sensitivity cases, IS92 S1 High Deforestation and IS92 S2 Reforestation. The IPCC IS92 S2 Reforestation case assumes a policy intervention to reforest and results in net carbon absorption after the year 2025 which increases to one PgC/yr by the end of the next century. The envelope of high deforestation cases is formed by two cases developed by Houghton (1991) while the envelope of low cases is formed by a Houghton (1991) case and the IS92 S2 Reforestation scenario.

Our Cases 2 and 3 examine the implication of general productivity growth shifts, with Case 2 maintaining crop and pasture productivity growth at 2.0 percent per year on average, rather than the steady decline to 1.5 percent per year assumed in our reference case. Case 3 assumes that productivity growth ceases all together. The resulting land-use change emissions trajectories mirror each other. As would be anticipated, high productivity growth in agriculture leads to significantly lower net emissions. The high productivity leads to reduced demands for land for agricultural products and livestock. This both reduces pressure to deforest and lowers the rental rate on land, leading to greater use of land for commercial biomass energy production. The cessation of agricultural productivity growth, Case 3, has the opposite implication. Growing incomes and population drive rental rates on land upward, increasing the pressure on forest lands and reducing the profitability of commercial biomass energy.

Cases 4 and 5 explore the implications of the cessation of productivity growth in either crops and pastures or forests and commercial biomass energy. In Case 4, biomass productivity ceases. This actually leads to a slight decline in land-use change emissions, as the reduced profit potential of this land use reduces pressure competition for land. But the higher cost of commercial biomass energy means a smaller share of the energy market and aggregate fossil fuel carbon emissions increase. The increase is modest, never exceeding 1.5 PgC/yr.

In Case 5 commercial biomass energy productivity is set at the same rate as the reference case, but crop and pasture productivity is assumed to cease. This results in a substantial increase in land-use change emissions, which exceed 3.0 PgC/yr in the middle of the next century. Total anthropogenic emissions are somewhat lower initially, but eventually exceed 3.0 PgC/yr by the end of the next century.

Interestingly, the biomass contribution is lower with higher biomass productivity but no crop or pasture productivity growth, Case 5, than for the case in which commercial biomass energy productivity ceases but crop and pasture productivity continues to grow, Case 4. In the former, Case 5, commercial biomass energy contributes approximately 36 EJ/yr in 2095, while in the latter, Case 4, commercial biomass energy contributes 52 EJ/yr in 2095.

The final two cases, Cases 6 and 7, which are characterized by significantly improved biomass productivity. Enhanced biomass energy productivity leads to higher land-use change emissions than in the reference case. The higher commercial biomass energy productivity, Case 7, is associated with higher land use change emissions. The increase in land use change emissions for Case 7 never exceeds 0.75 PgC/yr. The higher commercial biomass energy productivity means lower energy prices and an increase in the demand for commercial biomass energy. This in turn leads to higher rental rates on land and provides an incentive to bring more land into production. The effect on total carbon emissions, however, is strongly negative.

Commercial biomass energy accounts for 35 percent of total energy supply in Case 6, and 55 percent of total energy supply in Case 7. Year 2095 emissions decline from 19 PgC/yr in the reference case, Case 1, to 13.5 PgC/yr in Case 6, and to 4.8 PgC/yr in Case 7. Cumulative emissions are reduced in Case 6 by 25 percent and in Case 7 by 55 percent. The importance of these two cases is to indicate the power of technological development in the development of commercial biomass energy technologies. These technologies are not yet available and require further research and development efforts.

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Figure 2: COMPONENTS OF THE AGRICULTURE-LAND-USE MODEL

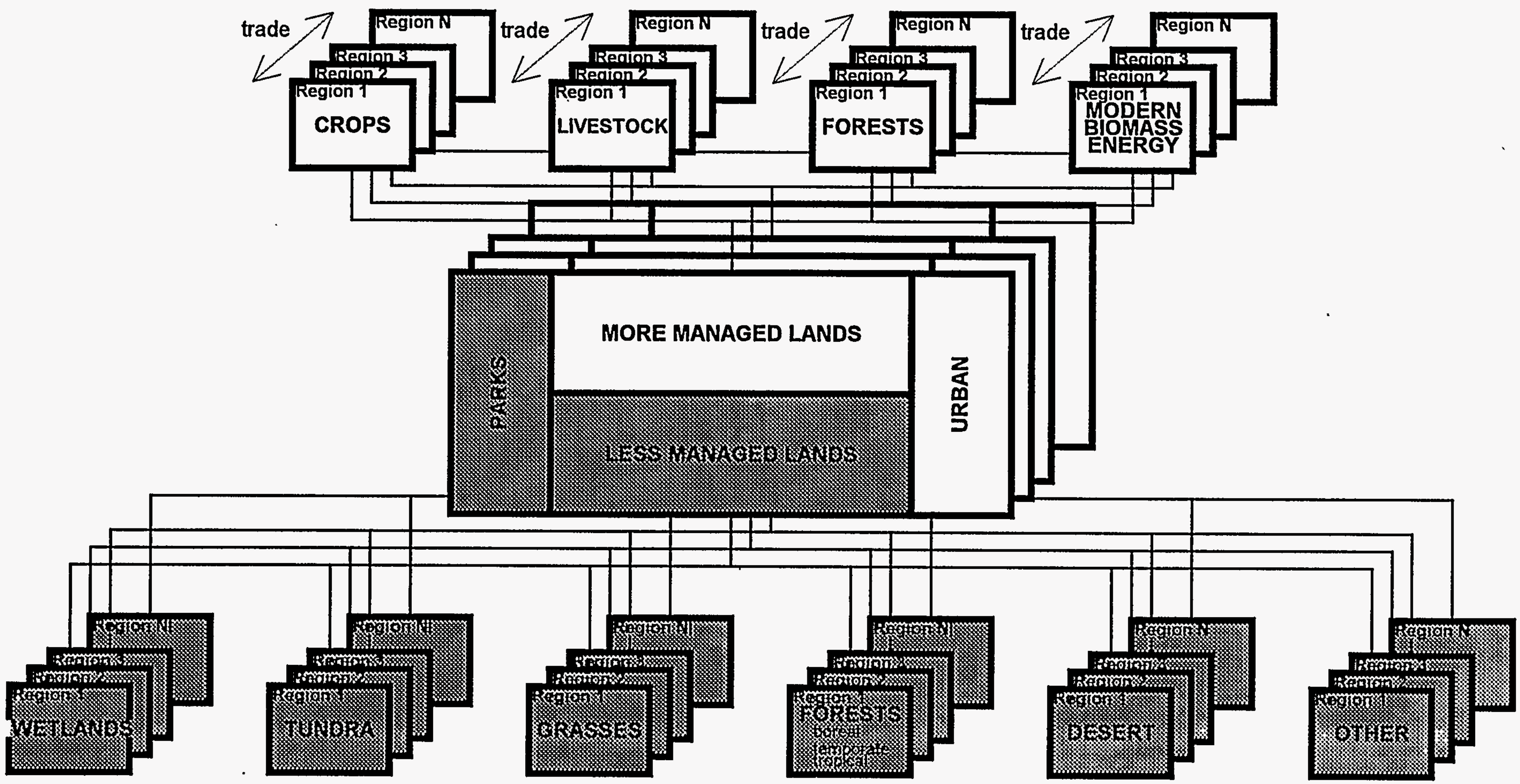
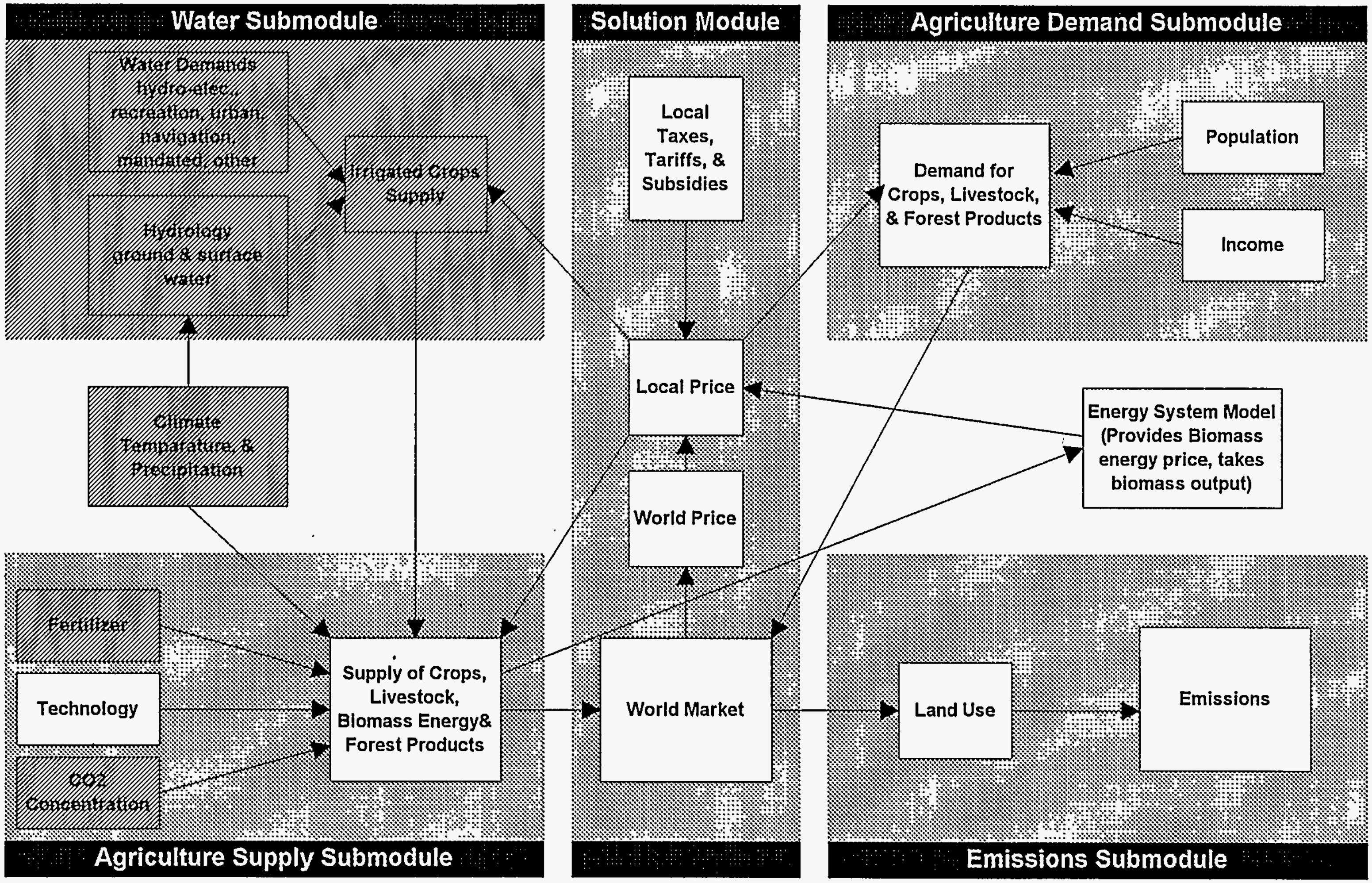


Figure 3: Agriculture-Land-Use-Water Module



Indicates that model component is not implemented in MiniCAM 2.0.

Figure 4: Global Agriculture, Forestry, and Livestock Production (MT)

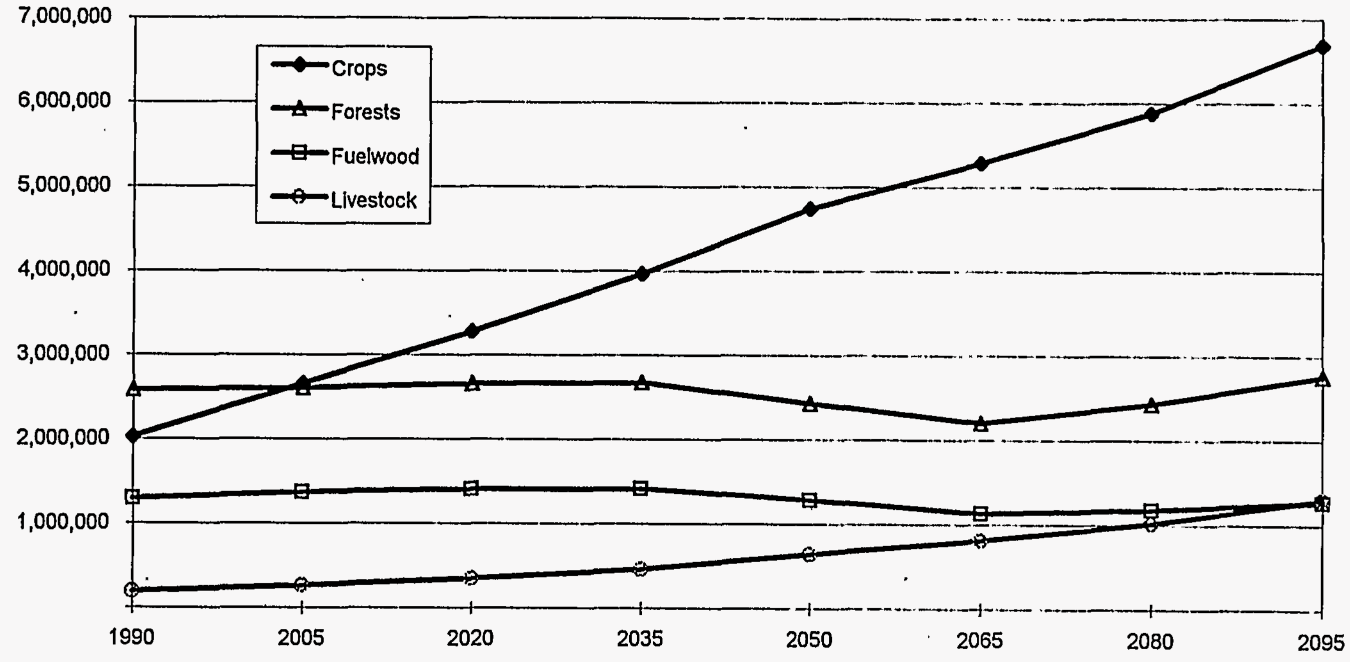


Figure 5: Global Consumption per Capita (T/cap/yr)

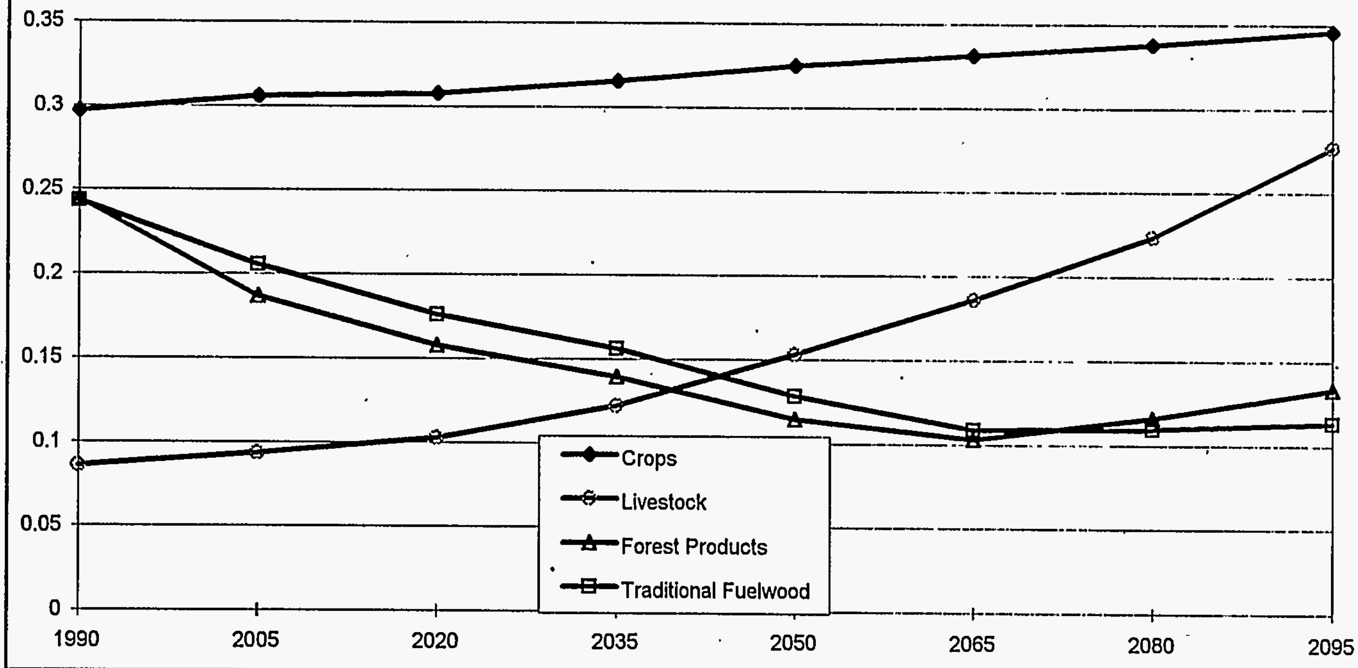


Figure 6: Commercial Biomass Energy Production By Region

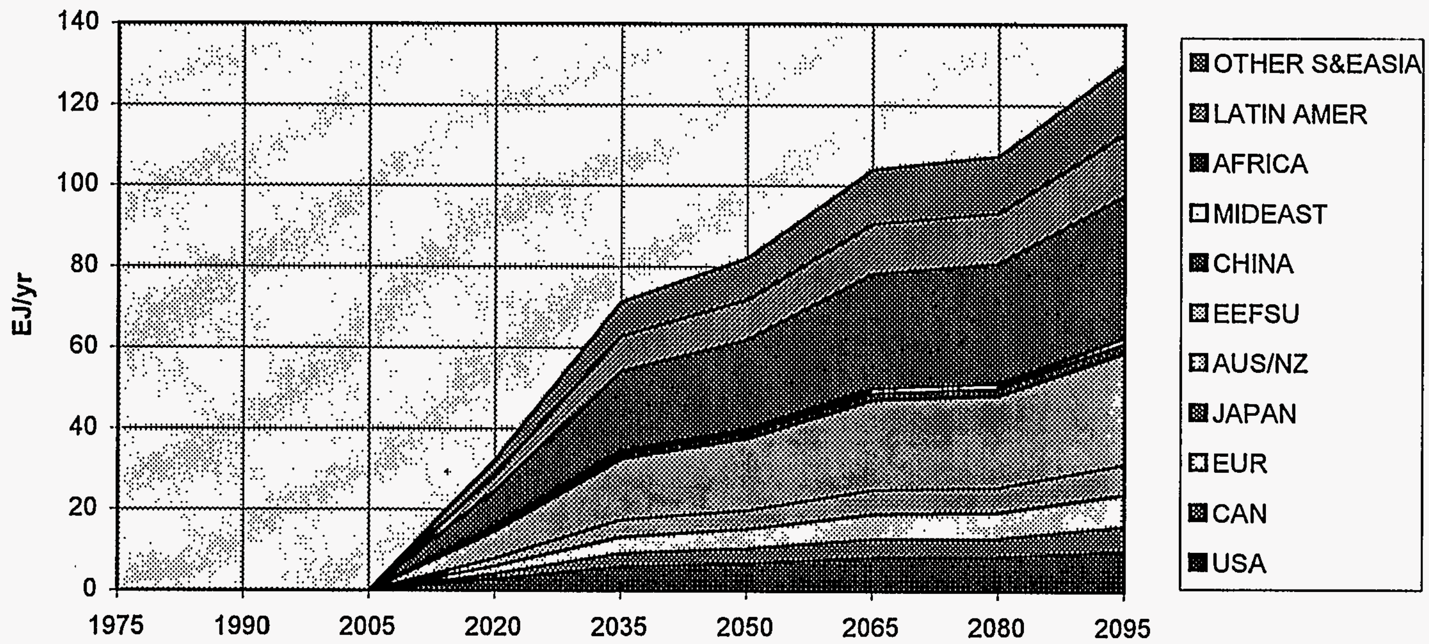


Figure 7: Commercial Biomass Trade

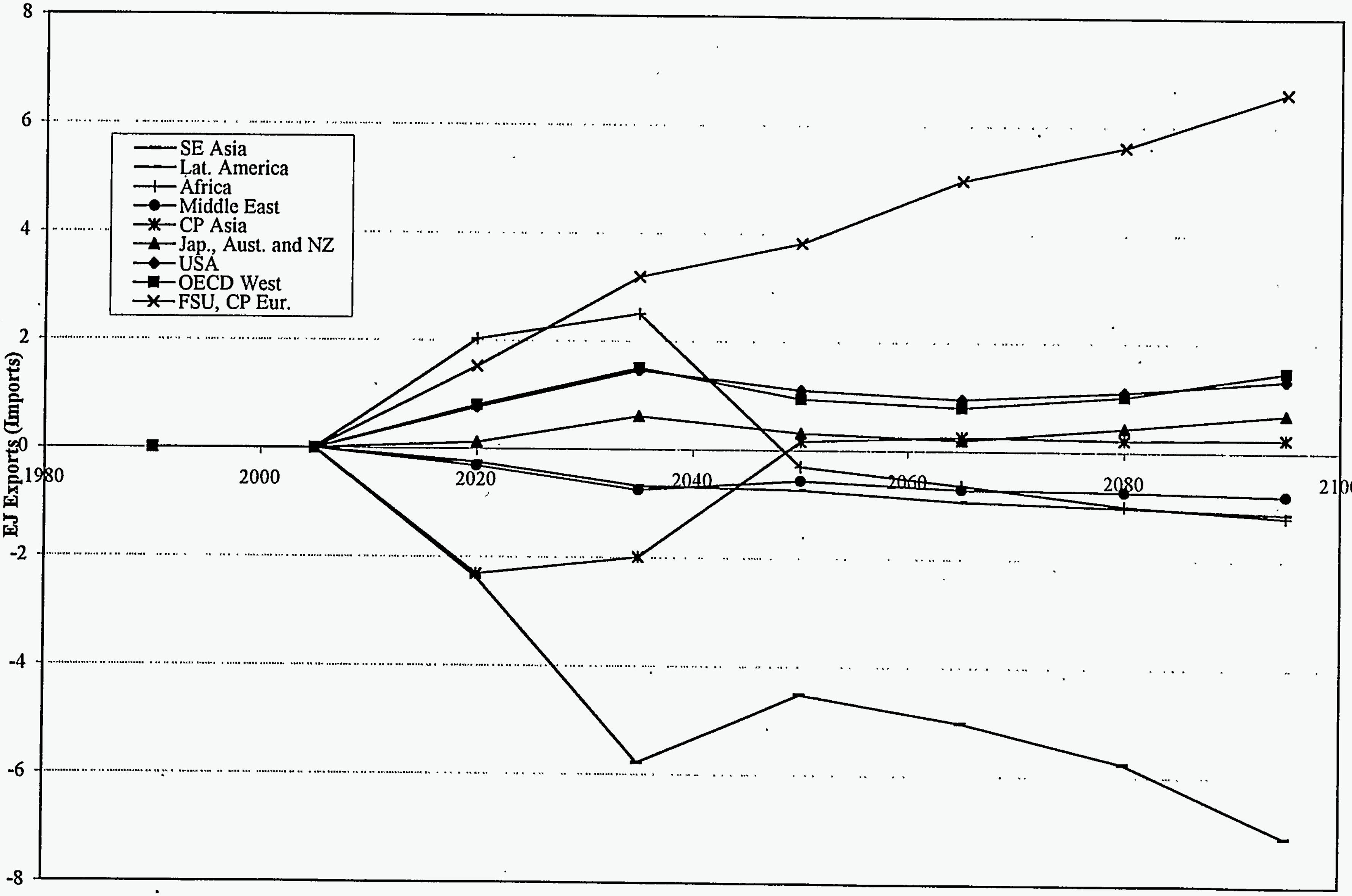


Figure 8: Global Land Use

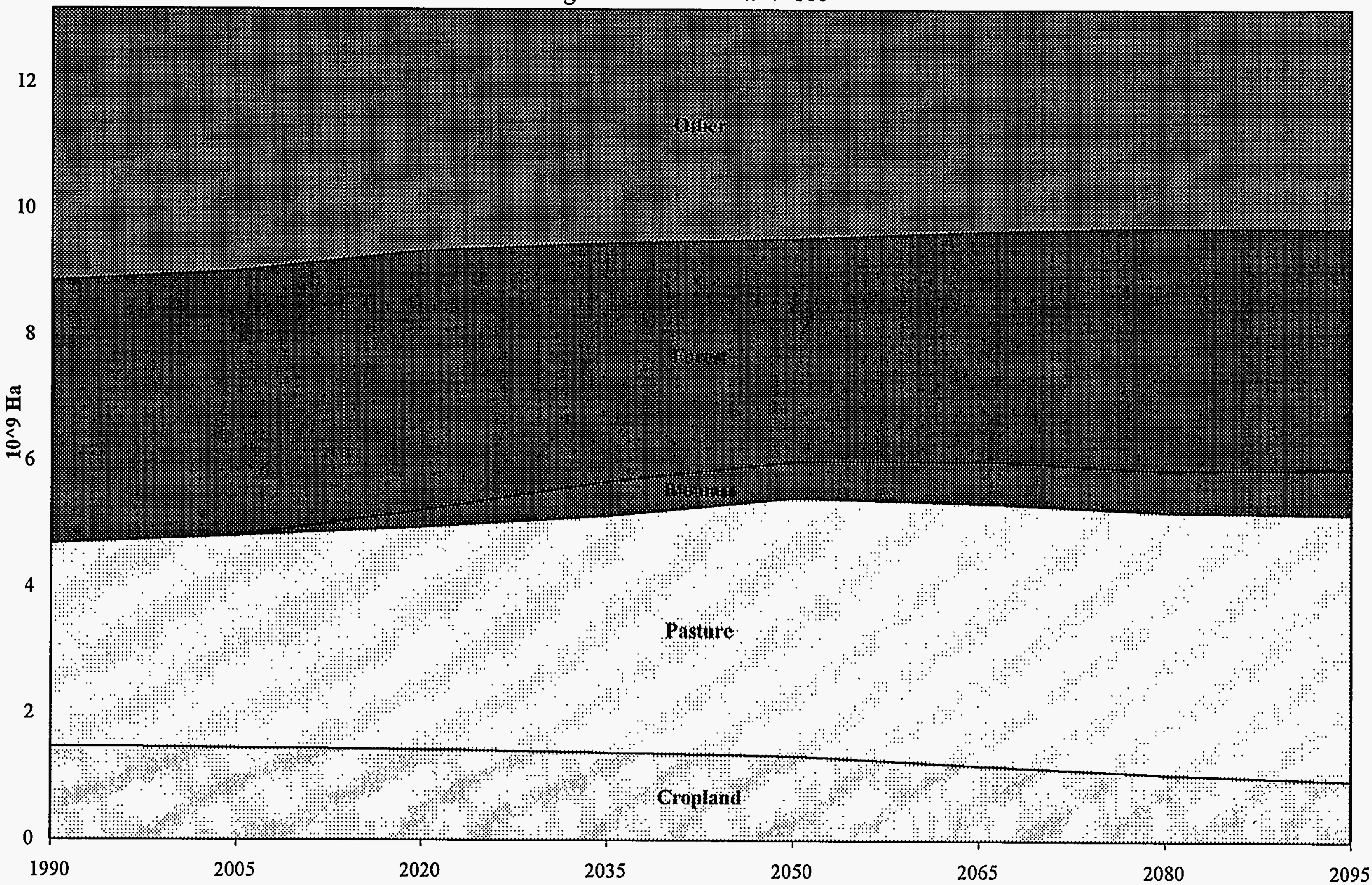


Figure 9: Reference Case Anthropogenic Carbon Emissions

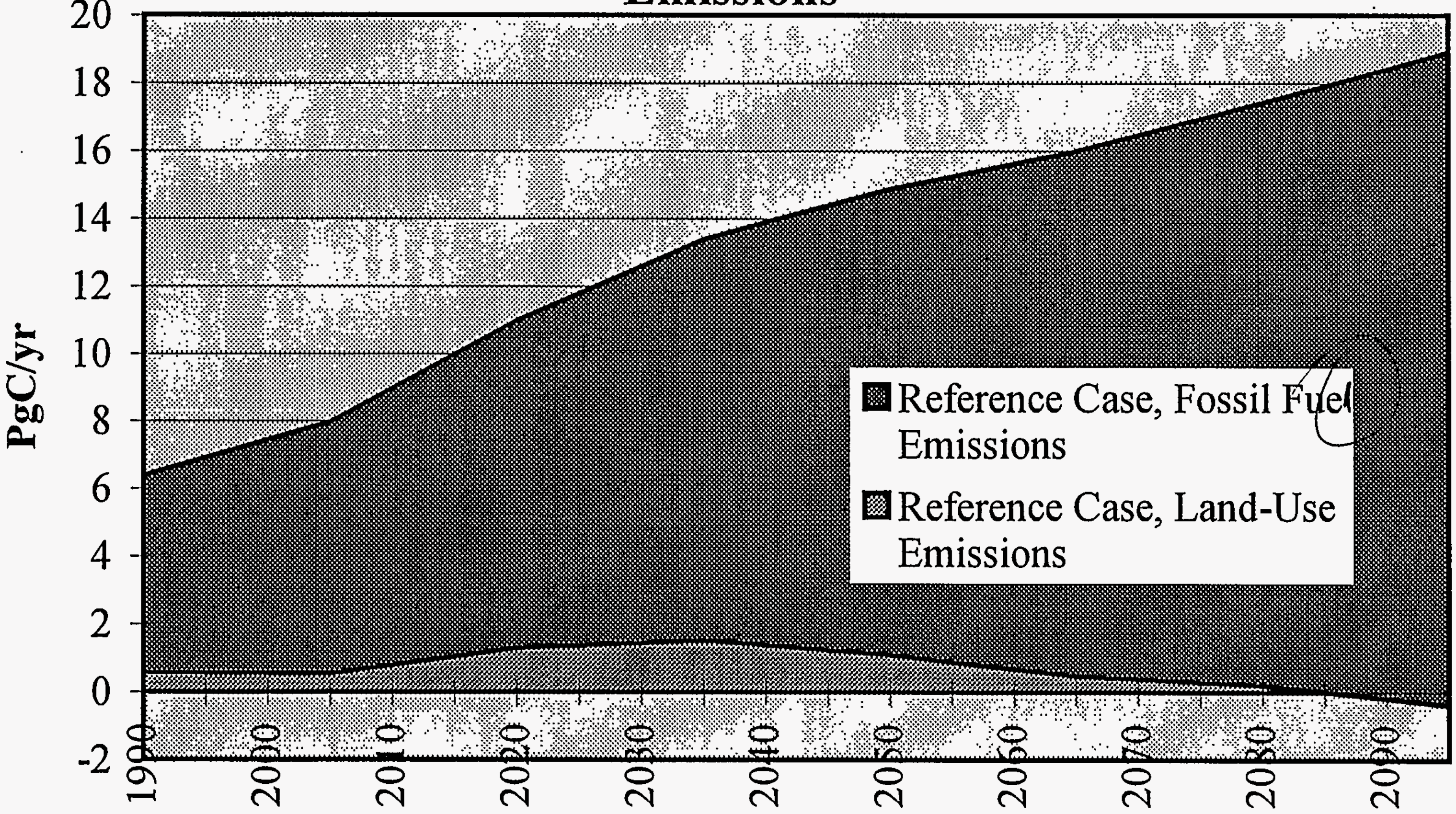


Figure 10: Landuse Change Emissions Scenarios from Various Studies

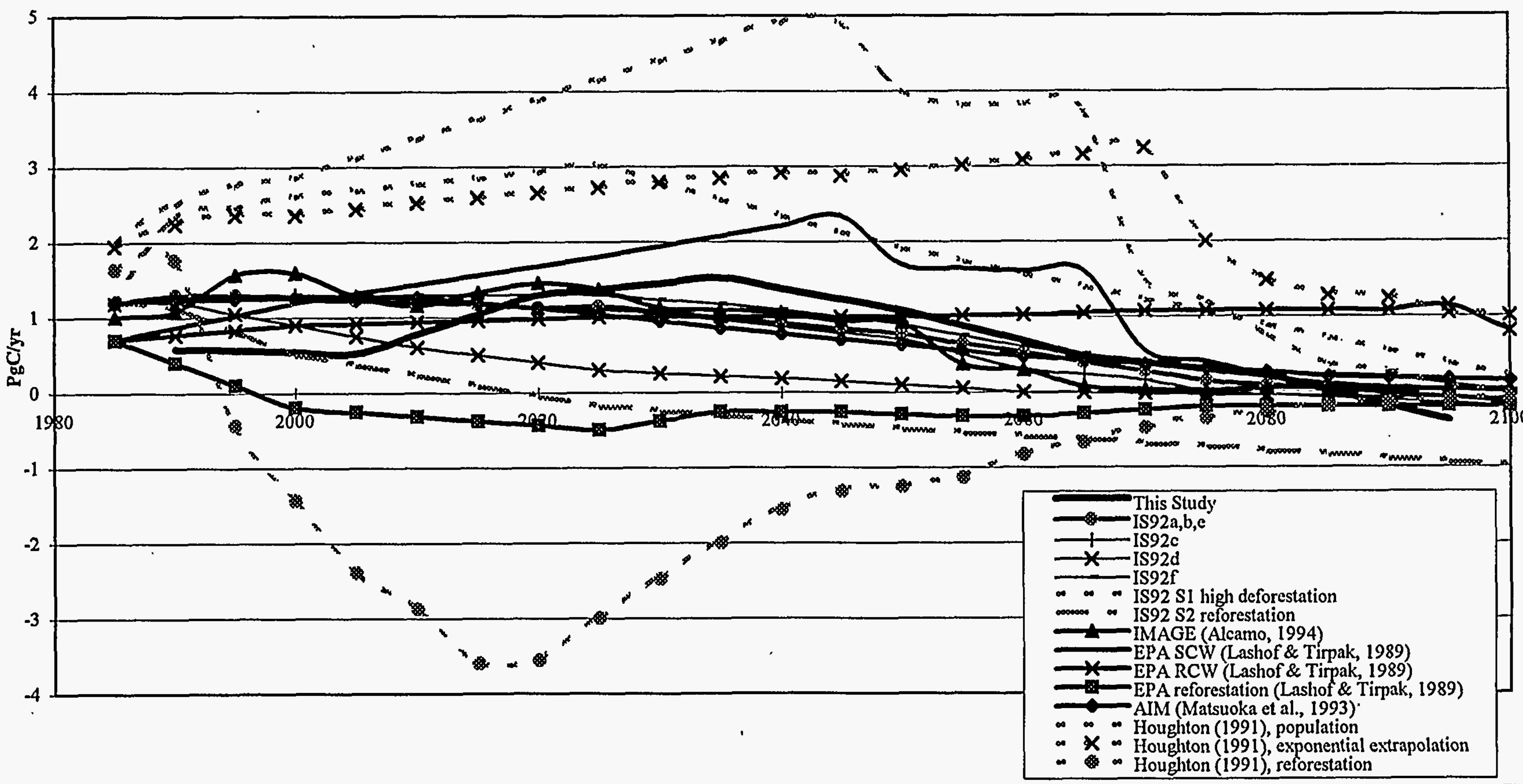


Figure 11: Land Use Change Emissions Sensitivity Cases

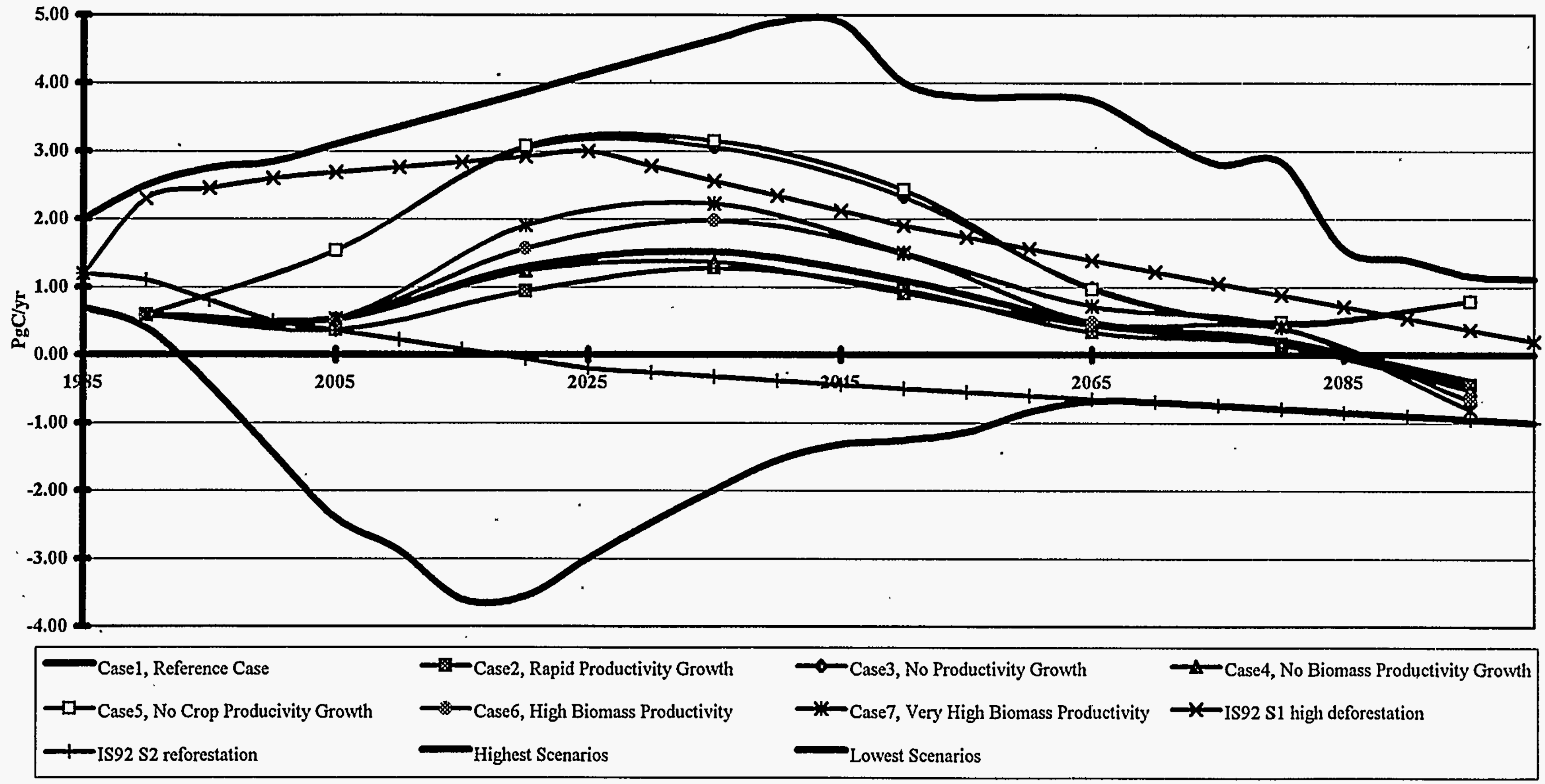


Figure 12: Total Net Carbon Emissions Sensitivity Cases