MODELING AGRICULTURE AND LAND USE IN AN INTEGRATED ASSESSMENT FRAMEWORK

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Abstract. The Agriculture and Land Use (AgLU) model is a top-down economic model with just enough structure to simulate global land-use change and the resulting carbon emissions over one century. These simulations are done with and without a carbon policy represented by a positive carbon price. Increases in the carbon price create incentives for production of commercial biomass that affect the distribution of other land types and, therefore, carbon emissions from land-use change. Commercial biomass provides a link between the agricultural and energy systems. The Integrated Assessment of Climate Protection Strategies (ICLIPS) core model uses AgLU to provide estimates of carbon emissions from land-use change as one component of total greenhouse gas emissions. 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. Significant carbon emissions from land-use change are present even in the reference scenario. An aggressive ICLIPS mitigation scenario results in carbon emissions from land-use change up to 800 million metric tons per year above the AgLU reference scenario.

1. Introduction

Projections of global greenhouse gas emissions over the next century show that the agricultural sector will likely play a significant role in potential future increases in radiative forcing and climate change. Greenhouse gas emissions associated with agriculture include methane, nitrous oxide, and carbon dioxide – with the flux of this last gas arising from deforestation. Conversely, the agricultural sector can reduce net emissions of carbon dioxide through the production of carbon-neutral biomass fuels to substitute for some portion of fossil fuels that would otherwise be used.

The Agriculture and Land Use (AgLU) model was developed to simulate global land-use change and the resulting carbon emissions in response to a carbon policy. Edmonds et al. (1996) constructed the first version of the AgLU model as an addition to the Edmonds–Reilly–Barns (ERB) model of energy consumption and carbon emissions. ERB contains world markets for oil, gas, coal, and commercial biomass (Edmonds and Reilly, 1985). AgLU adds markets for crops, animal products, and forest products. Commercial biomass provides the link between the energy structure of ERB with land use in AgLU. Recently, AgLU was transferred

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to the Integrated Assessment of Climate Protection Strategies (ICLIPS) modeling framework as a stand-alone agricultural model. AgLU is a partial equilibrium economic model with a base year of 1990 and 15-year time steps to 2095. Working at a global scale necessitates a relatively aggregate modeling approach. The world is divided into eleven regions, and the production of a composite crop, animal product, and forest product is simulated within each region.

Other global models of agriculture and land use include IMAGE (Integrated Model to Assess the Greenhouse Effect) (Alcamo et al., 1998), FARM (Future Agriculture Resource Model) (Darwin et al., 1995), and the Basic Linked System (Fischer et al., 1988) developed at the International Institute for Applied Systems Analysis (IIASA). These models are similar on the demand side: consumer preferences and income influence demand for agricultural products. However, the supply side of IMAGE stands in contrast to the other models with its grid-cell level of land-use detail and set of allocation rules for land use. FARM and the Basic Linked System use market-clearing prices to allocate land resources among competing uses, but do not match land use to specific geographic locations. While IMAGE has been used to illustrate the potential for modern biomass as an energy source globally (Leemans et al., 1996), the Forestry and Agricultural Sector Optimization Model (FASOM) was used to analyze forest carbon sequestration programs and options of biomass-based energy production within the United States. FASOM allows for land transfers between forestry and agriculture, recognizing that forestry decisions are inherently dynamic, spanning several decades (Adams et al., 1996).

At the core of AgLU is a mechanism to allocate land among crops, pasture, and forests according to the economic return from each land-use type in each region. A joint probability distribution is defined over yield in each alternative land use. Yield is measured in units of calories per hectare for crops and pasture. With additional information on prices and non-land cost of production, each landowner is assumed to select the land use with the greatest economic return calculated as revenue less non-land cost of production. With simplifying assumptions on the geographic distribution of yield, a reduced-form solution can be obtained for the share of total land in each region allocated to each land use as a function of prices and non-land costs of production. Carbon densities are then applied to each land-use category to provide an estimate of the carbon stock during each 15-year time step. Carbon emissions from land-use change are calculated as the difference in carbon stock between periods.

The land allocation methodology used here is adapted from Clarke and Edmonds (1993), which considers the related problem of selecting a set of energy technologies to produce a given energy service at minimum cost. Instead, we allocate land across agricultural activities to maximize economic returns to land owners. The spatially independent approach used here is quite different than the geographically detailed approach of the IMAGE model. Our approach is able to approximate the profit-maximizing behavior for landowners, and what that implies for international trade of agricultural products and land use. Our approach also provides relatively short computation time, which allows AgLU to reside within a larger modeling system that may need to iterate to an overall solution. However, we do not have the ability to link land-use change to a specific geographic area, and our simple probabilistic structure does not capture the true variability of land within a region. It is difficult to match the parameters of the joint probability distribution used by AgLU with the large amount of data available on soil and crop productivity.

The three primary drivers of land-use change are population growth, income growth, and autonomous increases in future crop yields. Even small changes in the rate of increase in future yields can have a large impact on the amount of cropland needed to maintain adequate diets. Changes in the regional composition of consumption in response to higher incomes can also be important, especially if people in developing countries increase per-capita consumption of animal products to the level seen today in the United States and Europe.

The AgLU model contains enough complexity to (1) provide estimates of carbon emissions from land-use change over the next century in response to changing populations, incomes, and agricultural technologies and (2) evaluate the role of commercial biomass and its impact on land use in a carbon-constrained world.

The next section describes the overall model structure. Following sections describe the determinants of demand and supply of agricultural products in AgLU, a sensitivity analysis of the response of biomass production to an increase in the carbon price, and links between the ICLIPS core model and AgLU.

2. Model Structure

The version of AgLU used with ICLIPS divides the world into eleven regions for consistency with other ICLIPS components (see Table I).

The AgLU model produces a composite crop, a composite animal product, a composite forest product, and commercial biomass. Agricultural data for base-year calibration were obtained from the Food and Agricultural Organization (FAO, 2000) of the United Nations. The composite crop is built up from FAO data on cereals, starchy roots, sugar crops, oil crops, fruit, and vegetables. Each individual crop is first converted from the original FAO units of kilograms to calories using weights with units of kilocalories per kilogram. Individual crops are then aggregated to a composite crop using units of calories. A similar procedure is used for animal products. The animal product composite is built up from FAO data on meat, animal fats, milk, and eggs. Forest products use the original FAO units of cubic meters.

AgLU contains markets for crops, animal products, and forest products. For crops, one world price brings global supply and demand into equilibrium. The forest products market is also cleared globally, with one world price. However, we also solve for a forward price in the forest market because of the time lag between planting and harvesting trees, described later in the section covering supply.

Table I
World regions in AgLU

NAM	North America (United States and Canada)
LAM	Latin America (including Mexico)
WEU	Western Europe
EEU	Eastern Europe
FSU	Former Soviet Union
MEA	Middle East and North Africa
AFR	Sub-Saharan Africa
CPA	China and Centrally-Planned Asia
SAS	South Asia
PAS	Other Pacific Asia
PAO	Australia, New Zealand, Japan

Animal products are split into eleven regional markets. Regional supply must equal regional demand, adjusted for trade in animal products between regions. Trade in animal products between regions is fixed at 1990 levels in AgLU. This assumption is reasonable given the relatively small amount of trade between regions in animal products, due mostly to high transport costs for these products.

Finally, each region is capable of growing commercial biomass, given a high enough biomass price. A carbon price, which in part determines the price received by growers of commercial biomass, is exogenous to AgLU. Every other market has an unknown price to be solved for in each model time step. In summary, the AgLU model has 14 prices determined by 14 nonlinear equations that equate supply and demand in each market. The 14 markets are:

- 1 world market for a composite crop,
- 11 regional markets for a composite animal product,
- 1 world market for a composite forest product,
- 1 world forward market for a composite forest product.

International trade is an important mechanism in AgLU that allows regions with a growing population, but limited amounts of unmanaged land that can be converted to agriculture, to maintain adequate diets. The composite crop in AgLU is traded freely among regions so that increases in global demand for crops are supplied wherever it is least expensive to grow them. Even though trade in animal products is limited in AgLU, trade in animal feed (from crops) provides a mechanism for indirect trade in animal products.

Figure 1 shows the amount of international trade in three food groups: crops consumed directly, processed crops, and animal products. Processed crops include sweeteners, vegetable oils, and alcoholic beverages. These aggregate food cate-

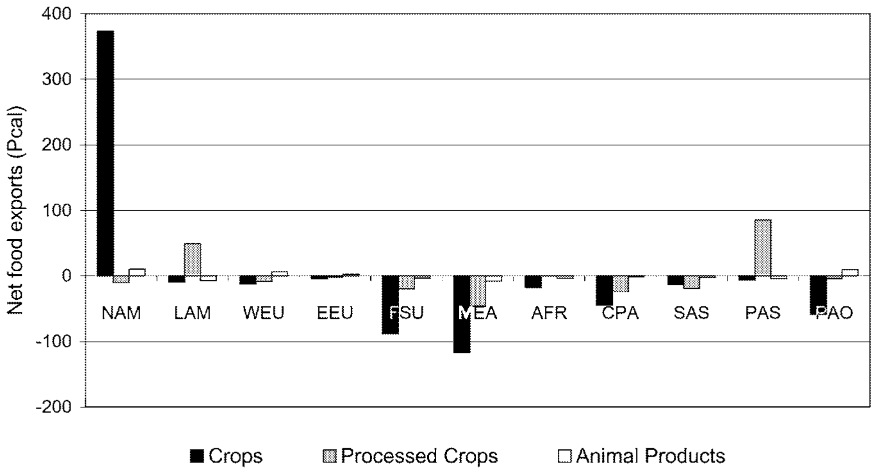

Figure 1. Net food exports in 1990. See Table I for the list of regions.

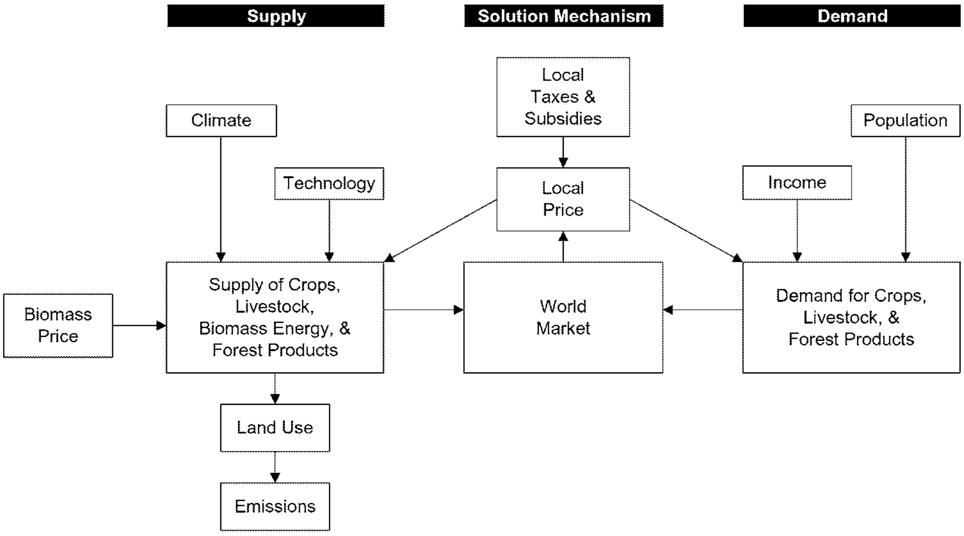

Figure 2. AgLU model structure.

gories are built up from individual foods listed in the FAO food balance tables. Units for all of the food groups in Figure 1 are calories to facilitate aggregation within, and comparison between, these categories. Data in Figure 1 are net exports, equal to exports less imports, which can mask offsetting imports and exports in a region. The greatest amount of trade takes place in the crops category, with North America exporting large amounts of crops to several other regions. As measured in calories, trade in animal products between regions is relatively small.

AgLU model structure is shown in Figure 2. Market prices influence both supply and demand, and AgLU searches over prices in each time step to bring supply and demand into equilibrium. A modified version of the Newton–Raphson search algorithm is used. This search procedure requires derivative information for supply and demand with respect to the unknown prices. Each iteration within the search procedure requires n model calls to calculate numerical derivatives, where n is the number of unknown prices. With this information on derivatives, a log-linear approximation to the supply and demand functions is created and a new set of trial prices is obtained by solving the log-linear system through matrix inversion. Five iterations are usually sufficient within each model time step. A full model run with eight time steps, five iterations per time step, and n model calls per iteration, requires a total of $40n$ model calls.

Supply of crops, biomass, and forest products is calculated as the amount of land allocated to that land use times average yield. Yields are influenced by exogenous assumptions on climate and technology. Population and income influence the demand for crops, animal products, and forest products.

3. Demand

Consumer demand for food creates direct demands for crops as well as indirect demands through animal products. FAO food balance data for 1990 were aggregated into three broad food categories: crops consumed directly, crops consumed indirectly as processed crops, and animal products. Direct crop consumption consists primarily of cereals, but also includes starchy roots, fruits and vegetables. Processed crops include vegetable oils from oil crops, sweeteners from sugar crops, and alcoholic beverages. Animal products include meat, milk, butter, eggs, and animal fats. As shown in Figure 3, consumption of processed crops and animal products varies greatly across regions. However, the sum of crops and processed crops stays within a range of 2,000 to 2,500 kilocalories per day per person across regions.

The demand equation for crops, processed crops, and animal products is

$$X_{ijt} = A_{ij} P_{ijt}^{\alpha_{ij}} Y_{ijt}^{\beta_{ij}} N_{jt} C_{ijt}\,, \quad i = \text{crops, processed crops, animal products}\,, \tag{1}$$

where j is a region index, t is time, X is quantity demanded, A is a constant to calibrate the price and income feedback terms in the base year, P is price, Y is per-capita income, N is total population by region, and C is calories consumed per person per day.

Final demand for agricultural products may vary over time in two ways. The first is through directly varying C as an exogenous input by region and food category, providing a simple way to create scenarios of alternative future diets. The second way is through the price and income elasticities in Equation (1). Care must be taken in setting price and income elasticities so that simulated consumption stays within a

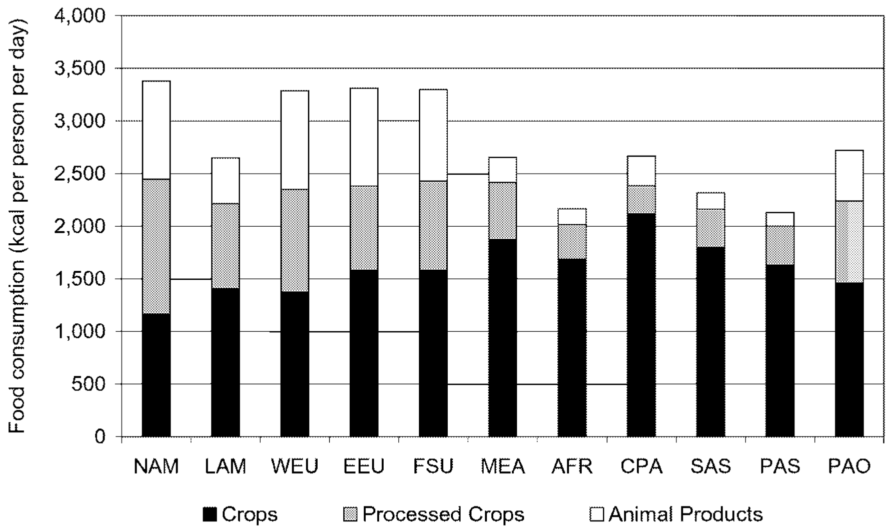

Figure 3. Food consumption by region in 1990. See Table I for the list of regions.

plausible range in each region and food category. Income elasticities for crops and processed crops are set to be small and positive, or zero. Similarly, price elasticities for these two food categories are set to be small and negative, or zero. Data from Figure 3 suggest that consumption of animal products is more responsive to income and price than is consumption of crops and processed crops. Price elasticities for animal products are negative and greater (in absolute value) than price elasticities for crops and processed crops. This price feedback on consumption of animal products is necessary to find an AgLU market solution for scenarios with slow rates of improvement in crop yield over time.

A broader view of global food supply and demand is shown in Table II, which is a simplified food use table in units of kilocalories per person per day derived from FAO food balances. Total production of crops, including crops used in the production of animal products, is much larger than final demand for crops. Table II is structured with each column representing a production or consumption activity, and each row containing inputs to these activities. For example, the first row of Table II shows all uses for crops. The first entry in the row for crops represents self-consumption as seed and waste; the third entry is the amount of crops used as feed in the production of animal products.

By comparing the number of calories of crops fed to animals with the calories of animal products consumed as food, we see that the global average efficiency of converting crops into animal products is roughly 37%. The efficiency would be even lower if we considered the caloric content of pasture used as feed. This points to the importance of preferences for consumption of animal products as a driver of future land-use changes.

We can also compare the number of calories of crops used to make vegetable oils, sweeteners, and alcoholic beverages to the calories of these processed crops

Table II
1990 Global Food Balance (kcal per person per day)

	Production activity			Final demand			Total production
	Crops	Processed crops	Animal products	Food	Other uses	Stock change	
Crops	344	748	1041	1726	51	49	3959
Processed crops	0	0	2	532	80	–4	609
Animal products	0	0	37	382	38	0	457

Source: FAO (2000).

consumed as food. This conversion process has a much higher efficiency than converting crops into animal products.

AgLU also computes demand for two types of forest products: industrial wood and fuel wood.

$$X_{ijt} = A_{ij} P_{ijt}^{\alpha_{ij}} Y_{ijt}^{\beta_{ij}} N_{jt}\,, \quad i = \text{industrial wood, fuel wood}\,, \tag{2}$$

where X is quantity demanded, P is price, Y is income, and N is population. The A term is used to calibrate base-year demands to historical data by region. Price per cubic meter is assumed the same for industrial wood and fuel wood. Income elasticity is positive for industrial wood and negative for fuel wood.

Demand for biomass is not computed directly. Instead, a price for biomass is exogenously supplied, which determines the amount of land dedicated to producing biomass as described in the following section on supply.

4. Supply

Supply of crops, biomass, pasture, and forest products is calculated as the amount of land allocated to each land use times average yield. Animal products are produced with a combination of crop-based feed and pasture. The following tree diagram shows how land is allocated among alternative land uses. During any model time step, some land is already committed to trees previously planted. Other land is allocated among crops/biomass, pasture, and newly planted trees. Crops and commercial biomass are grouped in a nest because we assume land for growing commercial biomass competes directly with land for growing crops. This nesting structure is reasonable for the case of a biomass crop such as corn or sugar cane that will be converted to liquid fuels.

The land allocation scheme used in the AgLU model is presented in Figure 4 and described in the following sections. First, the idealized equations describing all land parcels in a region are specified, followed by their transformation to aggregate equations that describe land allocation for an entire region. Selection of land use

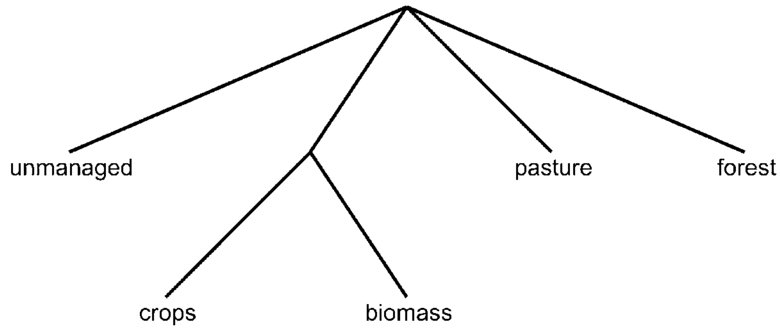

Figure 4. Land allocation in AgLU.

is based on maximizing economic return at each location. Profit per hectare is equal to revenue (yield per hectare times price received) less production cost (yield per hectare times non-land cost per unit of output). This relationship is shown in Equation (3), where i is an index for land-use type, j is a region index, and k is an index for geographical location within a region:

$$\pi_{ijk} = y_{ijk}\left(P_{ij} - G_{ij}\right), \quad i = \text{crops, biomass, pasture}. \tag{3}$$

Here, y_{ijk} is yield for land use i in region j at location k, P_{ij} is the price received for the product produced by land use i, and G_{ij} is the non-land cost per unit of output in land use i. The profit rate calculation for forest products is somewhat different because of the time lag between planting and harvest.

$$\pi_{ijk} = \frac{r}{(1+r)^{45} - 1} y_{ijk}\left(\widetilde{P}_{ij} - G_{ij}\right), \quad i = \text{forests}, \tag{4}$$

where r is the interest rate and $\widetilde{P}_{ij}$ is the price per cubic meter of forest products three model time periods (45 years) into the future. The profit rate expression for forest products includes a term that discounts future earnings into the present and levelizes those earnings over 45 years.

A joint probability distribution of yield is defined over each alternative land use within a region. Some locations may offer a high crop and pasture yield, but low forest yields. Other locations may show the opposite pattern, or other patterns. Given a joint probability distribution of yield, information on prices received, and non-land costs of production, it is possible to determine the share of land allocated to each use and the average yield within each land use.

4.1. LAND SHARES

This section describes calculations used within AgLU to determine the share of land allocated to each land-use type. In general, land use shares would be calculated numerically, by summing over the land distributions implied in Equations (3) and (4). In the usual integrated modeling context, however, we wish to work on large regional scales. We use instead a reduced-form expression for land shares that effectively sums over the index k in Equations (3) and (4). This derivation is described in the Appendix along with an explanation of the underlying statistical assumptions. An interesting feature of this land allocation mechanism is that for any given land use, average yield may fall as the amount of land allocated to that use increases. For example, if the most productive land is first allocated to crops, cropland can only expand into land less suitable for crops.

If all land within a region were allocated to a single use, say crops, then we could construct a distribution of crop yields, even though most of those yields would never be observed in practice. The average yield for a given land-use type, across all land, whether this land-use type is observed or not, is an intrinsic property of the yield distribution and does not vary with prices or land shares. This distribution is characterized by a scale parameter and variance, and covers all potential yields for a crop, whether observed or not. The scale parameter can be thought of as a type of average, such as the mean or mode. Equations in this section implicitly assume that such a yield distribution exists for each land use where yield varies by geographic location, and that geographic location captures variation across temperature, precipitation, available sunlight, soil quality, and slope of land.

Yield distributions may be correlated. For example, land that produces high yields for crops is likely to also provide high yields for commercial biomass. Land use i will be selected only at locations where its profit rate is greater than that of all alternative land uses. Given a joint probability distribution for yield across alternative land uses, the set of potential yields at any particular location can be considered a random sample from that joint probability distribution. Since yield is a random variable, profit rate as defined by Equation (3) or (4) is also a random variable.

The fundamental parameter that determines land shares is $\overline{\pi}_i$, the profit rate (annual earnings per hectare) evaluated at an average, or intrinsic, yield for land use i. By intrinsic yield, we refer to the scale parameter of the yield distribution, which could be the mean, mode, or some other point on the probability density function. We consider this an intrinsic parameter of the yield distribution because it is invariant with respect to prices or land-use shares, and is an average across all locations that a particular crop could possibly be grown. This parameter is allowed to vary between time steps to represent autonomous increases in yield over time.

With specific assumptions on the functional form of the yield distribution, the share of land allocated to use i is given by

$$s_i = \frac{\overline{\pi}_i^{1/\lambda}}{\sum_k \overline{\pi}_k^{1/\lambda}}, \tag{5}$$

where λ is a positive parameter that determines the rate that land shares change in response to a change in profit rate and the denominator is summed over all possible uses for land. See the Appendix for an interpretation of λ as a function of the variance of the yield distribution, and as a function of the correlation coefficient. For simplicity, the region index is suppressed in Equation (5) and all equations that follow. This allocation mechanism is convenient because greater profit rates imply greater shares of land, it can be calculated quickly, and the shares sum to one. The profit rate calculation required for Equation (5) is given by

$$\overline{\pi}_i = \overline{y}_i(P_i - G_i)\,, \quad i = \text{crops, biomass, pasture}\,, \tag{6}$$

where $\overline{y}_i$ is the intrinsic yield for land use i.

We note that this profit rate calculation for pasture requires a price for pasture-based feed $P_{pasture}$. AgLU calculates the price of pasture indirectly through the price of animal products and crops, both of which are solved for within the model. Given these two prices, $P_{pasture}$ is found by solving:

$$P_{animal} = P_{crops} \times FeedOut + P_{pasture} \times PastOut + G_{animal}\,. \tag{7}$$

FeedOut is the ratio of crop-based feed calories needed per calorie of animal product; *PastOut* is the ratio of pasture-based feed calories needed per calorie of animal product. As before, G is the non-land cost per unit of output.

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. This future price is determined by equating supply and demand in a market for forest products three AgLU time steps (45 years) in the future. The profit rate calculation for land allocated to forest products is analogous to Equation (4) and is given by

$$\overline{\pi}_{forest} = \frac{r}{(1+r)^{45} - 1}\overline{y}_{forest}\left(\widetilde{P}_{forest} - G_{forest}\right)\,, \tag{8}$$

where r is the interest rate and $\widetilde{P}_{forest}$ is the price per cubic meter of forest products three model time steps ahead. Two markets for forest products are brought into equilibrium within each AgLU time step. 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.

Current supply of forest products depends on the number of trees planted in the past. AgLU operates in 15-year time steps and assumes that tree lifetime is 45 years, or three model time steps. During any given AgLU time step, the vintage of trees that was planted three time steps previously is cut to provide current supply of forest products. Supply of current forest products is therefore fixed, and AgLU searches for a price that brings global demand for industrial wood and fuelwood into equilibrium with this fixed global supply.

4.2. OBSERVED YIELD

In the previous section, we showed how land-use shares were calculated using profit rates evaluated at an intrinsic yield for each land use. Intrinsic yield should be thought of as an average yield across all possible locations where a crop could be grown, regardless of the actual land use selected by profit-maximizing land owners. This intrinsic yield does not vary with prices or land shares. However, the average yield of land for any given land type that survives the land allocation process is always greater than the corresponding intrinsic yield. We call this the *observed* average yield.

In modeling practice, intrinsic yields and base-year prices are used as calibration parameters to match base-year data on observed average yield and land allocated to each use. The following equations show how the observed average yield is calculated for each land-use type.

An observed average profit rate for all land within a region is written as a function of the profit rates evaluated at intrinsic yields. This is shown in Equation (9) where k is an index across land-use types. The observed average profit rate is greater than any of the individual (unobserved) profit rates:

$$\hat{\pi} = \left[\sum_k \overline{\pi}_k^{1/\lambda} \right]^{\lambda} . \tag{9}$$

An interesting result is that observed average profit rates are equal across land-use types as indicated in Equation (10). This result is not derived here, but is a consequence of assuming economic optimization. Clarke and Edmonds (1993) derive a similar result in the context of selecting a set of cost-minimizing energy technologies.

$$\hat{\pi}_i = \hat{\pi} \,, \quad i = \text{crops, biomass, pasture, forest.} \tag{10}$$

We exploit this result to calculate an observed average yield for each land use analogous to Equation (6). The observed average yield for crops, biomass, and pasture is given by

$$\hat{y}_i = \frac{\hat{\pi}_i}{P_i - G_i} \,, \quad i = \text{crops, biomass, pasture.} \tag{11}$$

Therefore, the observed average yield is defined to be the yield at which the profit rate is equal to $\hat{\pi}_i$. Average yield is multiplied by the amount of land, given by the land share from Equation (5), to determine supply.

4.3. NESTED MODEL

Previous equations cover the non-nested case for allocating land. However, Figure 4 shows a nested structure for land allocation. The top nest allocates land to a crops/biomass aggregate, but does not allocate land between them. The lower nest allocates land between crops and biomass depending on their relative profit rates. The share of land allocated to crops within the crops/biomass nest is given by

$$\frac{s_{crops}}{s_{crops} + s_{biomass}} = \frac{\overline{\pi}_{crops}^{1/\lambda_2}}{\overline{\pi}_{crops}^{1/\lambda_2} + \overline{\pi}_{biomass}^{1/\lambda_2}} . \tag{12}$$

If we calculate the following profit rate for the crops/biomass composite:

$$\overline{\pi}_{crops/biomass} = \left[\overline{\pi}_{crops}^{1/\lambda_2} + \overline{\pi}_{biomass}^{1/\lambda_2}\right]^{\lambda_2} , \tag{13}$$

then it can be used in Equation (5), the land share equation for the top nest, and in Equation (9), the observed average profit rate for all land uses. If the exponent term λ from the top nest is equal to λ_2 from the lower nest, then the land share equations collapse to a single nest. A single nest is used for the case where the correlation coefficient is the same between all yield distributions. If not, a nested model is used.

4.4. TECHNICAL CHANGE

All of the $\overline{y}_i$ parameters are actually functions of time according to

$$\overline{y}_i(T) = \overline{y}_i(0) \prod_{S=1}^{T} (1 + \gamma_i(S))^{STEP} . \tag{14}$$

T is an integer that represents the model time period, where $T = 0$ during the base year of 1990. Since the model runs in fifteen-year time steps (i.e., $STEP = 15$), $T = 1$ represents 2005. Equation (14) provides a way to simulate exogenous increases in yield, especially for crops. Crop yields will likely increase in the future, but the rate of increase is uncertain. We simulate increases in AgLU crop yield in a range of 0.0% to 1.5% per year, with the amount of land needed for crops varying widely in later years depending on this assumption.

5. Sensitivity Analysis

Land use in AgLU is sensitive to population growth, the price of biomass fuels, productivity improvements in crops over time, and changes in diet. For ICLIPS, we are particularly interested in the response of land use to the price of biomass fuels. Here, we consider a generic biomass crop converted to a liquid fuel, with a parameterization that approximates a corn to ethanol process. See Goldemberg et al. (1993) and Wyman et al. (1993) for descriptions of various biomass to liquid fuel processes including sugar cane to ethanol and corn to ethanol. In a market equilibrium, the price paid for biomass liquids will equal the price of refined

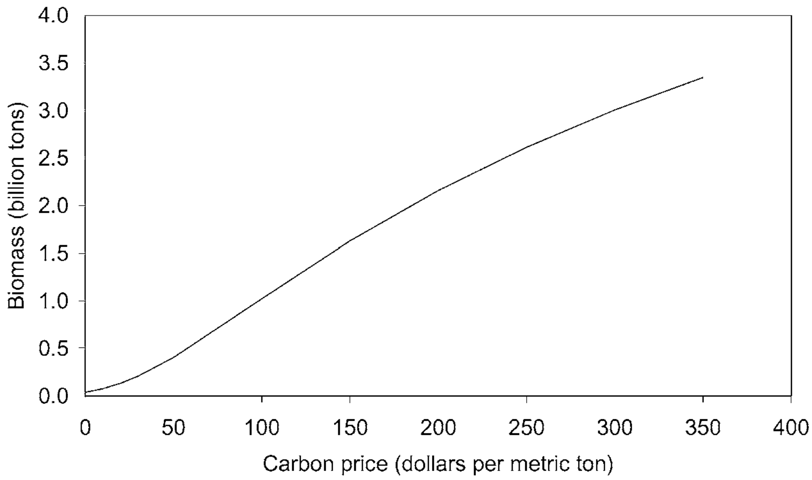

Figure 5. Supply of biomass in 2050 as a function of carbon price.

petroleum-based liquids. Therefore, the price received for a biomass-based fuel depends on the price of crude oil, the cost of refining oil to a transportation fuel (*OilTranCost*), and the carbon content of oil valued at the price of carbon:

$$P_{biofuel} = P_{oil} + OilTranCost + P_{carbon} \times OilCarb\,. \tag{15}$$

Biomass-based liquid fuels are competitive with oil when the price of biomass feedstock, adjusted by its net energy content after conversion (*EtoBio*), plus the cost of transformation to liquid fuel (*BioTranCost*), is equal to the price received for biomass-based fuels:

$$P_{biomass}/EtoBio + BioTranCost = P_{biofuel}\,, \tag{16}$$

where $EtoBio = 10$ GJ of biofuel per metric ton of biomass; $P_{oil} = \$3.50$ per GJ; $OilTranCost = \$2.00$ per GJ; $BioTranCost = \$4.00$ per GJ; $OilCarb = 15$ kg C per GJ.

EtoBio represents the energy efficiency of converting solid biomass to a liquid fuel. If we solve for the price of biomass feedstock using Equations (15) and (16), we obtain the price received for biomass, in dollars per metric ton, as a function of the crude oil price and the carbon price:

$$\begin{aligned} P_{biomass} \;=\; & EtoBio \times (P_{oil} + P_{carbon} \times OilCarb \\ & + OilTranCost - BioTranCost)\,. \end{aligned} \tag{17}$$

Figure 5 shows how AgLU responds to a carbon price in 2050 while holding other parameters, including the price of crude oil, constant. All of the scenarios in this section assume a 0.5% annual rate of improvement in crop productivity.

Figure 6 provides a series of graphics depicting global land use, first with a carbon price of zero, next with a carbon price that increases linearly to $100 per

Table III
Sensitivity of land area in 2050 to rate of change in crop yield (billion hectares)

Annual rate of change in yield	Cropland	Pasture	Managed forest	Commercial biomass	Unmanaged land
0.0%	2.83	2.07	1.13	0.00	3.42
0.5%	2.37	2.01	1.16	0.00	3.90
1.0%	2.07	1.94	1.18	0.01	4.25

ton in 2050 and then is constant, and finally with a carbon price that increases linearly to \$200 per ton in 2050 and constant thereafter.

Summary land-use data, compiled by the World Resources Institute (WRI, 1992), was used to set up 1990 land allocations. The WRI land categories are cropland, pasture, forest land, other land, and wilderness. Total world land (13.1 billion hectares), less wilderness (3.5 billion hectares) leaves 9.6 billion hectares to allocate between managed and unmanaged land. The amount of cropland by region in 1990 is taken directly from WRI (1992) as 1.5 billion hectares. However, we have split the amount of pasture and forest reported by WRI into managed and unmanaged for AgLU.

World population is growing rapidly until about 2050, requiring additional cropland and pasture land, even though crop yields are assumed to grow at 0.5% per year. After 2050, population growth slows, allowing crop yields to keep up with demand. The biomass wedge in Figures 6b,c keeps increasing after 2050 even with a constant carbon price, and hence a constant price received by producers of biomass fuel crops. However, the price of biomass crops is increasing relative to the price of other crops, which are falling in the second half of the century in these simulations.

Land use is quite sensitive to the assumed annual increases in crop yields. Table III presents simulated land use in 2050 for three annual rates of change in crop yield. As crop yields decrease, the additional land required for food is taken primarily from unmanaged land.

AgLU begins simulation in 1990 and operates with 15-year time steps. Even though data for the first time step of 2005 are not available, it is still possible to compare recent data with the AgLU trend between 1990 and 2005. Increasing population and rising incomes during the first time period, offset somewhat by improved crop yields, contribute to an increase in the amount of land for crops and pasture and a decrease in forestland. This trend appears in all regions through international trade. However, this does not match well with recent forestland increases in the United States, and this global average trend understates deforestation in South America. Comparing model simulation with recent history provides insights

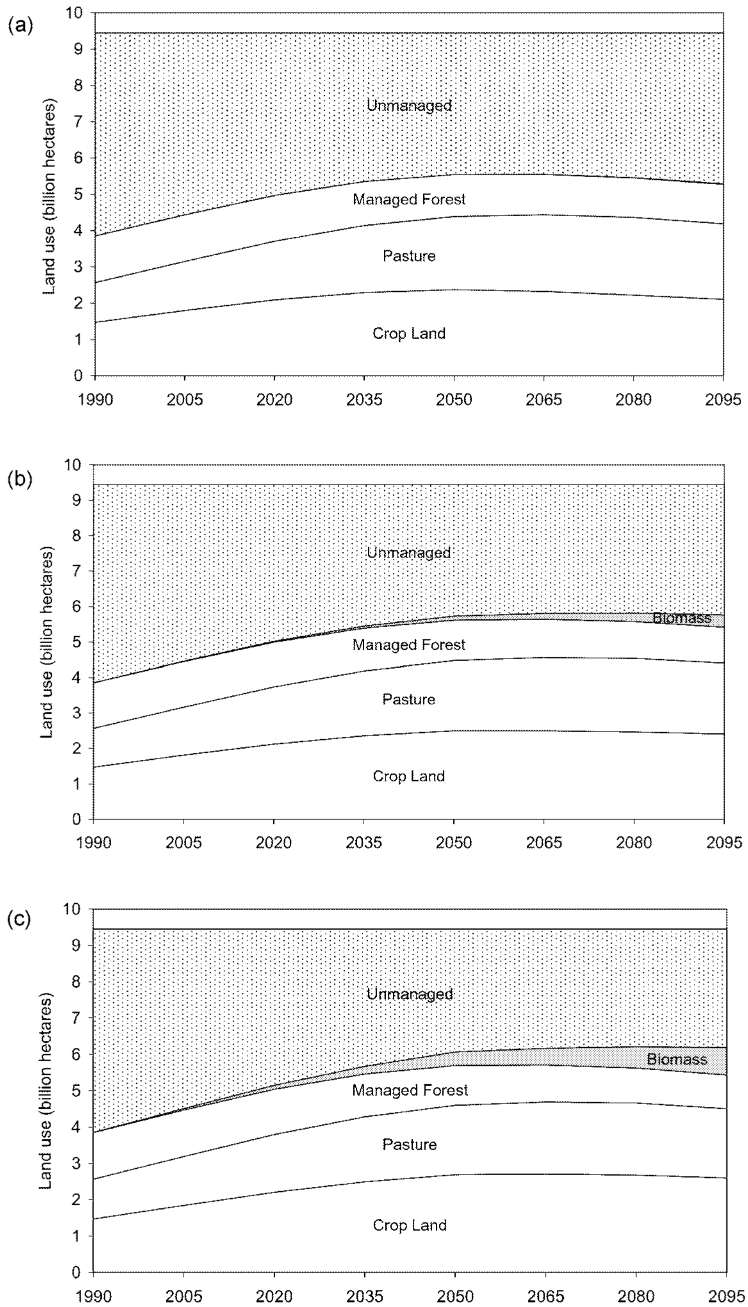

Figure 6. Land-use change under different scenarios of carbon price: (a) reference land-use scenario; (b) moderate carbon price; (c) high carbon price.

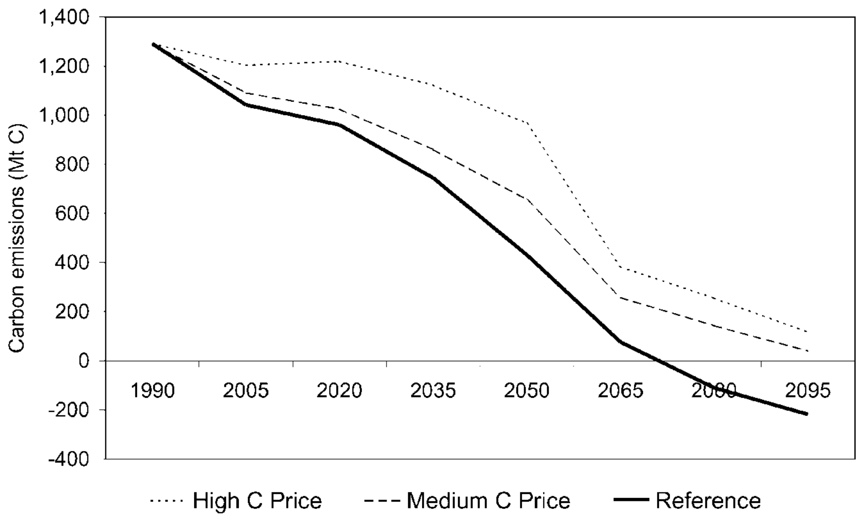

Figure 7. Carbon emissions from land-use change.

and exposes weaknesses in the model structure, especially with regard to trade barriers and regional food security.

Population and income growth are set exogenously in AgLU to match assumptions embedded in other ICLIPS components. The rate of crop productivity growth is also set exogenously with common rates of improvement across regions. There is room for improvement in this area, as it may be more plausible to assume convergence in crop yields toward current best practice, or going beyond best practice with breakthroughs in biotechnology. Such considerations would provide a better story behind changes in crop productivity, which profoundly influence simulated land use.

The final step is to calculate carbon emissions due to land-use change. 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. Results of these calculations are shown in Figure 7. Carbon emissions from land-use change start at a level of 1,300 million metric tons in all three cases. They decrease afterwards, while the reference case demonstrates the largest rate of decrease. Emissions from land-use change under a carbon policy do not decrease as rapidly as more land is used for the production of biomass.

6. Linking AgLU to ICLIPS

In this section, we focus on the interaction between the land-use change model and the other parts of the ICLIPS model, mainly the core model, comprising the economic and the climate model (see Toth et al., 2003). Specific routines are written to

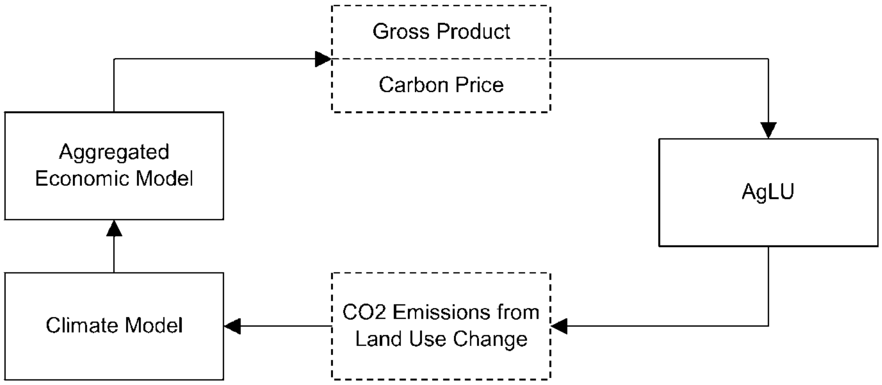

Figure 8. Data flow between AgLU and the ICLIPS core model.

link AgLU and the ICLIPS core model, which are written in different programming languages and run on different hardware platforms. At run-time, the ICLIPS core model calls AgLU iteratively, sending data on GDP growth by region and the time path of the global carbon price. The resulting emissions profile for CO_2 from land-use change is sent back to the core model, changing the climate protection strategy. Within a single iteration, complete model runs with AgLU and the core model are carried out successively.

The exchange of data between the relevant ICLIPS components is shown in Figure 8. Data on gross domestic product determines per capita incomes that, along with population, drive demand for agricultural products. The carbon price directly influences the biomass price (Equation (17)). The changing biomass price alters biomass production.

Figure 8 also shows how AgLU can be run as a stand-alone model. Once a time path of gross domestic product is specified for each region, the remaining key input is the carbon price, which can be provided exogenously or set to zero for land-use simulations without a carbon policy.

Due to a combination of the demand effect triggered by changes in gross product and the supply effect triggered by the carbon price, land allocation is changed according to the mechanism explained in previous sections on AgLU demand and supply. AgLU then generates a new profile for CO_2 emissions from land-use change by accounting for changes in carbon stock by land use.

Given a climate protection goal, the higher the emissions from land use, the lower the emissions allowed from the energy sector. In this way, land-use change emissions impact not only the climate system but the economic system, too. In order to further reduce emissions from the energy system, the carbon price will increase and economic growth is reduced.

While the effect on economic growth in terms of gross product output is rather small, the carbon price may vary significantly. Model output converges after a few iterations. Table IV demonstrates high fluctuations of carbon prices and emissions

Table IV
Convergence of the linked model

	Carbon price ($ per t C)					Global carbon emissions from land use (Gt C)				
	Iteration number					Iteration number				
	1	2	3	4	5	1	2	3	4	5
2005	104	134	141	141	140	1.03	1.59	1.84	1.90	1.90
2020	158	234	243	243	242	0.95	1.31	1.70	1.72	1.72
2035	200	247	252	251	250	0.73	1.11	0.92	0.89	0.88
2050	183	211	215	214	213	0.21	0.42	0.29	0.28	0.28
2065	147	160	162	162	161	–0.15	0.00	–0.14	–0.15	–0.15
2080	106	108	112	112	112	–0.35	–0.27	–0.40	–0.38	–0.38
2095	98	113	123	123	123	–0.24	–0.08	0.05	0.12	0.12

between the first iterations and convergence in the final iterations. Here, the core model runs in cost-effective mode (cf. Leimbach and Toth, 2003). The carbon price is derived from the emission permit trading system.

We now present results for two exemplary scenarios that illustrate how strongly different requirements for emissions reductions affect land-use change and biomass production. Scenario 1, presented in Table IV, indicates relatively high carbon prices, between $100 and $250 per metric ton of carbon, which result from a quite ambitious climate policy of meeting the WBGU climate window (i.e., a maximum temperature change of 2 °C and maximum temperature change rate of 0.2 °C per decade) while restricting reduction options to energy-related CO_2 only. Non-CO_2 emissions are assumed to follow the same path as IPCC IS92a.

A second scenario (Scenario 2) is created by assuming that non-CO_2 emissions are held constant from 1990 onwards, but otherwise equal to Scenario 1. Carbon prices peak in 2055 at $30 per metric ton of carbon. This peak is much lower and somewhat later than in Scenario 1 (see Table IV). The temperature change rate threshold is the cause of these peaks in both scenarios. Due to the increasing radiative forcing of non-CO_2 gases in Scenario 1, this threshold becomes binding earlier. CO_2 emission reductions are strongly required and the marginal value of a unit of carbon increases. After managing to slow down the rate of temperature increase, the requirements for further carbon mitigation are partly relaxed. Carbon prices decline to a lower level that is just high enough to force further reductions in order to stay within the absolute temperature change threshold. This threshold usually becomes binding at the end of the model time horizon in the year 2200. Restricting climate policy to the absolute temperature change guardrail only will result in a continuously increasing carbon price profile.

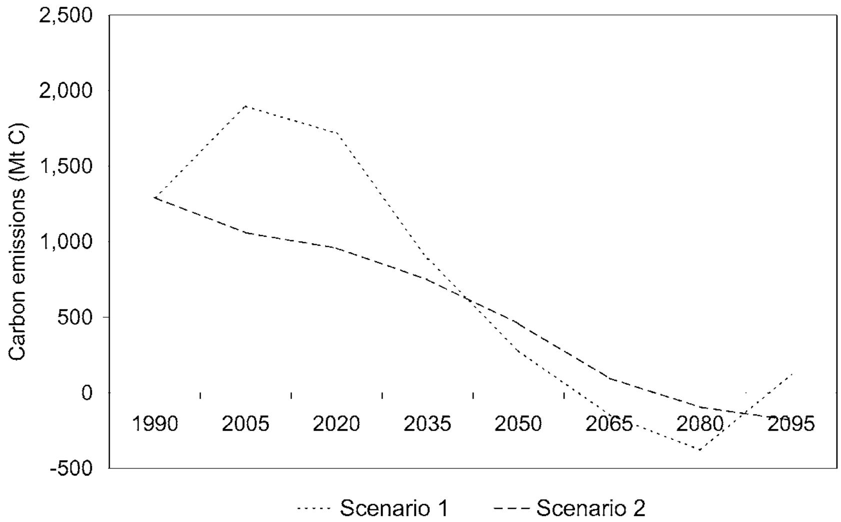

Figure 9. Carbon emissions from land-use change.

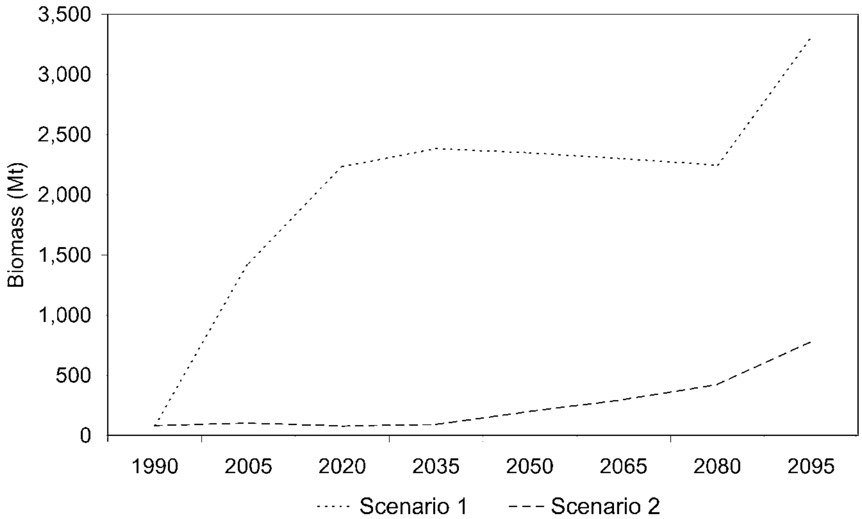

Figure 10. Biomass production.

The large differences between carbon prices of these two scenarios lead obviously to different emission profiles as well as different biomass production trajectories. This is shown in Figures 9 and 10. While an ambitious climate policy, associated with a high carbon price, is likely to force drastic reductions of industrial CO_2 emissions, there may be a negative secondary effect of increased emissions from land-use change.

Carbon emissions from land-use change increase to 1.9 Gt C in 2005, resulting in increased radiative forcing and early risk of exceeding the temperature

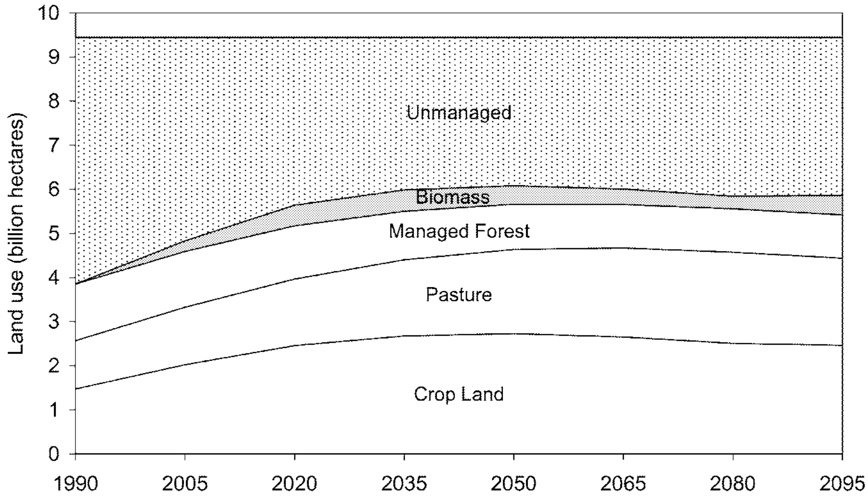

Figure 11. Land allocation (Scenario 1).

change threshold in Scenario 1. Scenario 2, in contrast, demonstrates a continuously declining trend. Because the carbon price is so low in Scenario 2, carbon emissions are nearly the same as in the reference case of Figure 7.

Figure 10 gives a hint to the causes of the high emission level of Scenario 1 in the early periods. Due to the high carbon price, an attractive biomass price motivates farmers to invest in biomass production. With the lower carbon price of Scenario 2, biomass production is attractive only in the later periods, when less area is required for crop production due to population stabilization and increasing crop yields. If the investment in biomass production is performed with a jump globally as in Scenario 1, biomass plantations may replace large forested areas.

The amount of land allocated to different uses under Scenario 1 is presented in Figure 11. Crop land, pasture land, and biomass land increase at the expense of forestry land and unmanaged land. Positive net emissions will occur most of the time due to the loss of carbon from forested areas. This also holds for Scenario 2. However, this effect is amplified in Scenario 1 due to the additional biomass production, which on the other hand helps to mitigate carbon emissions from fossil fuel combustion. According to the model result, the share of biomass land on the total amount of managed land is between 5% and 10% from 2005 onwards.

The results from Scenario 1 might be extreme and, with regard to the timing, even unrealistic. However, the risk of increased carbon emissions from land-use change should be considered with large-scale conversions of land to biomass crops. Policymakers should keep this effect in mind, so that the effect of higher carbon prices does not lead to a biomass-oriented policy that contradicts its own objectives.

7. Conclusions and Future Directions

Edmonds et al. (1996) set out to construct a top-down global model of agriculture and land use that considers the possible expansion of biomass-based fuels in response to an aggressive policy to limit global greenhouse gas emissions. That first version of AgLU provides the minimal amount of detail needed to create a link between the energy and agricultural systems. AgLU is now adapted, with a revised land allocation methodology, to accept information directly from the ICLIPS core model, and report output on carbon emissions from land-use change back to the ICLIPS core model. First model results show that a consequence of an expansion of land allocated to biomass crops is, at least temporarily, an increase in carbon emissions from land-use change. This represents a form of leakage, offsetting some of the emissions reductions obtained by reduced fossil fuel consumption. Emissions from land-use change should therefore enter the accounting balance when evaluating the emission reduction potential of biomass energy production. This version of AgLU assumes that any land conversion reaches steady state carbon intensity within the 15-year time step. Some processes, such as conversion away from tilled agriculture, clearly take longer than 15 years. We are addressing this dynamic issue in current model development.

International agreements that create markets for carbon emission rights will likely influence land use. In this paper, we consider the possibility of biomass-based fuels displacing fossil fuels in response to a carbon price. Lambin et al. (2001) provide an interesting discussion of other determinants for several classes of land-use change. For example, tropical deforestation may be influenced by decisions to extract timber for foreign revenue or by government policies to settle a sparsely populated frontier.

AgLU is designed to capture essential features of the economics of carbon mitigation and land-use change, including the notion that productive agricultural land is limited, that landowners select the land use that maximizes economic returns, and that international trade in grain allows for efficient allocation of land between world regions. AgLU is therefore an example of constructing a model to address a particular question. However, the aggregate structure of AgLU is unable to match the geographical and process-specific detail that a bottom-up model of agriculture or forestry can provide.

Planned enhancements for AgLU are intended to provide a better description of the variability of land quality, and to introduce water constraints for irrigated agriculture. Both of these goals would be made easier by splitting AgLU regions into subregions. Subregional agricultural supply can be added asymmetrically to the model, with some regions having more geographical detail than others, depending on data availability. For the United States, we are considering hydrologic unit areas as the basis for decomposition. Some of the regions will be unconstrained in terms of water, and some will have a limited supply of water for irrigated crops. Another enhancement, already in progress, is to split the composite crop into several crops, such as wheat, rice, coarse grains, and oil crops. These enhancements together would provide a way to test the ability of AgLU to simulate actual crop patterns, such as the dominance of corn in the United States corn belt.

Acknowledgements

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Appendix: Land Allocation Methodology

Clarke and Edmonds (1993) describe a methodology for selecting among competing energy technologies in a competitive energy market based on geographically heterogeneous cost distributions. At any particular geographic location, the minimum-cost technology is selected. Here we derive an analogous result, but for a geographic distribution of profit rate instead of cost.

The cost per unit of output for each energy technology in Clarke and Edmonds is described by a Weibull distribution, and the authors refer to the Weibull scale parameter as the *intrinsic cost* of a technology. Clarke and Edmonds derive a market share equation that is essentially the same as Equation (5) of this paper, except for the substitution of a profit rate for an intrinsic cost and the sign of the exponent. The Clarke–Edmonds market share equation provides a greater share as cost decreases; Equation (5) in this paper provides a greater market share as profit rate increases.

The Weibull distribution is convenient for models that minimize cost because the distribution of the minimum extreme of a Weibull distribution is again Weibull. However, our problem in this paper is to maximize a profit rate, which suggests using a Gumbel distribution because the maximum extreme of a Gumbel distribution is again Gumbel.

Using notation from Bury (1999), the univarite Gumbel distribution is defined as

$$f(x;\mu,\sigma) = \frac{1}{\sigma}\exp\left\{-\frac{x-\mu}{\sigma} - \exp\left\{-\frac{x-\mu}{\sigma}\right\}\right\} \quad \sigma > 0\,, \tag{A.1}$$

where μ is the mode of the distribution and σ is a scale parameter. If a random sample is drawn from each of several distributions with identical scale parameters but different modes, then the probability of selecting the *i*th distribution is given by

$$prob_i = \frac{\exp\left(\rho^{-1}\sigma^{-1}\mu_i\right)}{\sum\limits_k \exp\left(\rho^{-1}\sigma^{-1}\mu_k\right)}, \quad 0 < \rho \leq 1\,, \tag{A.2}$$

This says that the distribution shifted furthest to the right, or with the greatest average value, has the highest probability of being selected. Notation here is similar to that of Amemiya (1985). See Amemiya for a discussion of these types of distributions in qualitative response models, often referred to as logit models. Equation (A.2) considers the possibility that the distributions are correlated, where ρ is a function of the correlation coefficient r:

$$\rho = \sqrt{1-r}\,. \tag{A.3}$$

If we consider only the random samples that survive this selection process, they also are distributed Gumbel and the average (mode) of this distribution is $\hat{\mu}$, which is calculated using

$$\exp(\hat{\mu}) = \left[\sum_i \exp(\rho^{-1}\sigma^{-1}\mu_i)\right]^{\rho\sigma}. \tag{A.4}$$

It is possible to write (A.2) and (A.4) as closed-form expressions because we started with a Gumbel distribution. Equations (A.2) and (A.4) are only approximate for other distributions. Note that if we substitute

$$\mu_i = \ln \overline{\pi}_i \tag{A.5}$$

into (A.2), we obtain

$$s_i = \frac{\overline{\pi}_i^{1/\rho\sigma}}{\sum\limits_k \overline{\pi}_k^{1/\rho\sigma}}\,, \tag{A.6}$$

which becomes Equation (5) if we let

$$\lambda = \rho\sigma\,. \tag{A.7}$$

Similarly, we obtain Equation (9) when we substitute (A.5) into (A.4). Here, we are trying to describe the implicit assumptions that justify the use of share Equations (A.6) or (5). So far we have shown that share Equation (A.6) can be derived if we accept substitution (A.5). Next, we describe the assumptions needed to derive (A.5). If we write the profit rate calculation in logarithmic form, then

$$\ln \pi_i = \ln y_i + \ln(P_i - G_i)\,. \tag{A.8}$$

Assume that $\ln y_i$ is distributed Gumbel with mode η_i and scale parameter σ. Then $\ln \pi_i$ is distributed Gumbel with mode

$$\mu_i = \eta_i + \ln(P_i - G_i)\,. \tag{A.9}$$

The share equation operates as if the logarithm of profit rate has a Gumbel distribution and the mode of this distribution is μ_i. Next define

$$\overline{y}_i = \exp(\eta_i)\,. \tag{A.10}$$

This just tells us where $\overline{y}_i$ must lie on the distribution of crop yields. (A.10) can be substituted into (A.9) to obtain

$$\mu_i = \ln \overline{y}_i + \ln(P_i - G_i)\,. \tag{A.11}$$

Using Equation (6), we can write

$$\mu_i = \ln \overline{\pi}_i\,, \tag{A.12}$$

which is the same as (A.5). We have covered only the non-nested case in this Appendix. See Amemiya (1985) for examples of nested logit models. The advantage of using these share equations is that, given somewhat restrictive assumptions on the distribution of crop yields, we can calculate land shares immediately using Equation (5). Otherwise, an exact solution of the land-share problem requires numeric integration.

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