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GCAM 3.0 Agriculture and Land Use: Data Sources and Methods

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December 2011

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GCAM 3.0 Agriculture and Land Use Modeling: Data Sources and Methods

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Abstract

This report presents the data processing methods used in the GCAM 3.0 agriculture and land use component, starting from all source data used, and detailing all calculations and assumptions made in generating the model inputs. The report starts with a brief introduction to modeling of agriculture and land use in GCAM 3.0, and then provides documentation of the data and methods used for generating the base-year dataset and future scenario parameters assumed in the model input files. Specifically, the report addresses primary commodity production, secondary (animal) commodity production, disposition of commodities, land allocation, land carbon contents, and land values.

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1 Introduction to Agriculture and Land Use in GCAM 3.0

This report provides an overview of the data processing methods used in the generation of the input data set to the agricultural and land use components of GCAM 3.0, including references to all source data used, as well as assumptions, calculations, and methods used to generate the model inputs. The current section provides a brief overview of the context of the agriculture and land use components of the model; more comprehensive documentation can be found in Wise and Calvin (2011).

What primarily distinguishes GCAM 3.0 from previous versions is the ability to run the model with variable-length time steps, and the sub-regionalization of land use. While shorter timesteps can be used to capture desired near-term dynamics (e.g. policies with a specified start year), GCAM is still typically used as a long run model—running a century in 5-year steps. While the sub-regional representation of land use substantially changes the data read into the model, in terms of the overall modeling approach, the changes to this component should be considered evolutionary rather than an abrupt departure from previous versions. However, these changes, by design, do bring about a substantial increase in the ability to model crops and land use decisions and implications in much more physical, technological, and spatial detail, while still maintaining tight integration with the rest of GCAM.

In the core version of GCAM 3.0, the model data for the agriculture and land use parts of the model is comprised of 151 subregions in terms of land use, based on a division of the extant 18 types of agro-ecological zones (AEZs), which are derived from work performed for the GTAP project (Monfreda et al, 2009), within each of GCAM's 14 global geo-political regions (see Figure 1.1). Within each of these 151 subregions, land is categorized into approximately a dozen types based on cover and use (see Figure 1.2). Three of these types—tundra, desert, and built-up land—are not considered available for any other uses. The remaining land types are all subject to land use change over time according to changes in future profit rates. The different land use types include several types with natural vegetation such as unlogged forests and ungrazed grasslands, as well as commercial forests, pastures, and croplands. Approximately twenty primary agricultural commodities (including five bioenergy crops) are currently modeled, with yields specific to each of the 151 subregions. The model is designed to allow specification of different options for crop management for each crop in each subregion, though this capability is not used at present. Note also that the model structure allows for other regional breakdowns besides the AEZs.

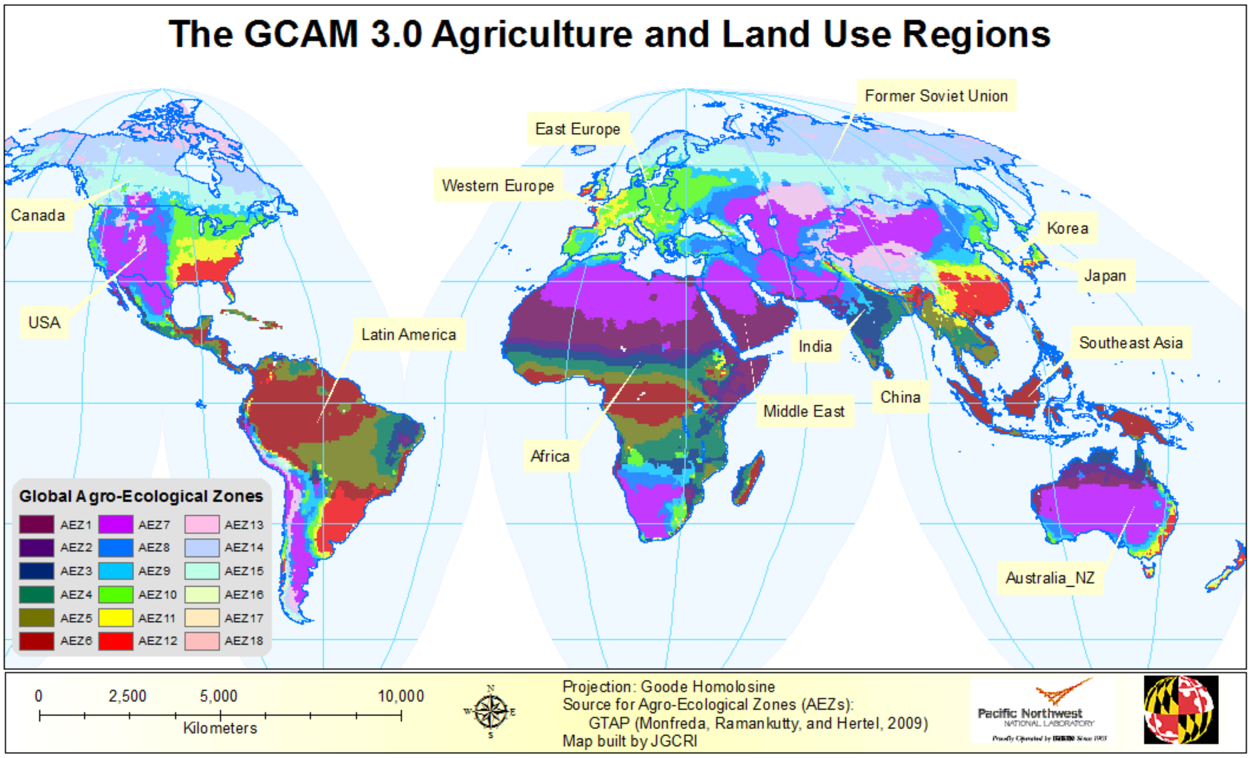

Figure 1.1 GCAM 3.0 agriculture and land use regions

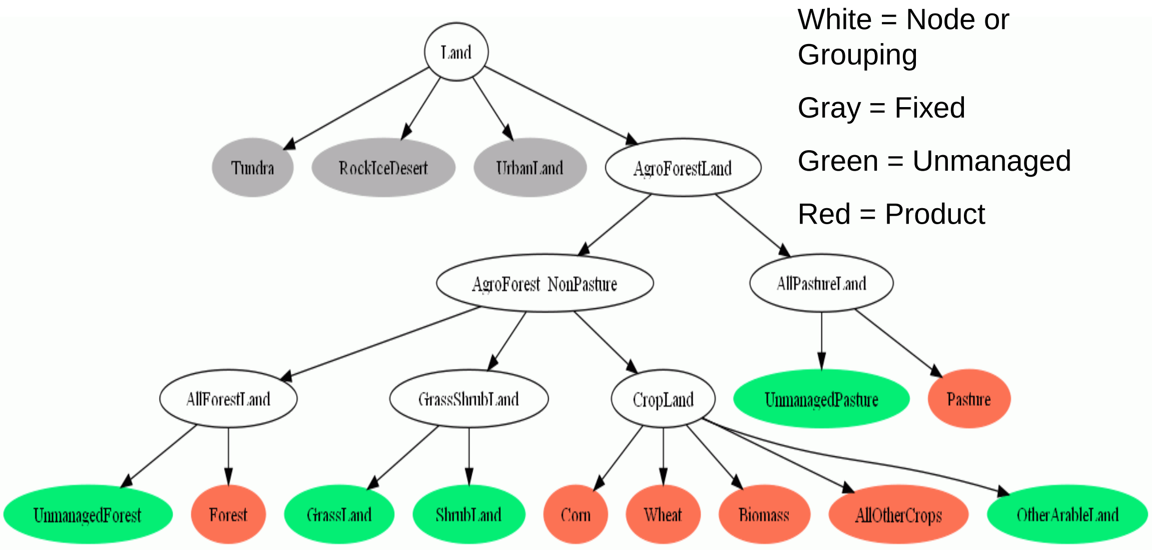

Figure 1.2 Land use types and land nesting in GCAM 3.0

The economic modeling approach for GCAM agriculture, forest, and land is that of an integrated economic equilibrium in the products, sectors, and factors that are modeled. Markets, for products such as corn or wheat, must be cleared so that supplies are equal to demands in each model period. Depending on the product or on user specifications, markets can be cleared globally, regionally, or across groups of regions. GCAM 3.0 is not considered a general equilibrium model and as such does not incorporate a closed system for the world economies as a whole. Instead, the focus for GCAM agriculture and land use modeling has been on incorporating more detail in the sectors that it does model, with physical representations of entities such as crops, technologies, resources, and land.

Although it is convenient to discuss the GCAM agriculture and land use component as if it were a distinct model, it is in fact completely integrated and intertwined with the rest of GCAM. For example, entities such as agricultural markets and crop technologies share much of the same model code and behavior as energy markets and technologies. GCAM's economic equations and solution procedures completely integrate all agriculture and energy markets at once, and in application make no distinction as to which sector each market comes from. Some aspects, such as the economic sharing of land, are specific to agriculture and land use. However, the same general approach to modeling specific technologies and solving for economic equilibrium of all supplies and demands that is used in the GCAM energy markets is used here.

The remainder of this document focuses on the generation of the input data set to GCAM 3.0. Broadly, the land use component consists of a variety of land types, several of which are involved in production of modeled primary commodities. These primary commodities have any of the following dispositions in GCAM: net exports to other regions, food (human consumption), feed (consumption by animals used in secondary commodity production), biofuel production, and other uses. Secondary (animal) commodity production is modeled by a range of production technologies characterized by input-output coefficients on feed, linking the produced animal commodities to the land. Biofuel production is modeled for a number of agricultural crops. Food consumption is tracked in calories per person, and all other uses are tracked in simple fashion, completing the mass balances for any commodity.

2 Commodity Production

2.1 Primary Commodities

Primary commodity production refers to all plant commodities: crops, roundwood, pasture grass, and purpose-grown bioenergy. This section describes all input parameters for the production technologies of these goods.

2.1.1 Agricultural Commodities

Primary agricultural commodities considered in GCAM are listed in Table 2.1.

Table 2.1. Agricultural commodities in GCAM.

Commodity	Description
Corn	
FiberCrop	Crops used primarily for fiber purposes
FodderGrass	Grasses used for fodder
FodderHerb	Non-grass fodder (e.g. legumes)
MiscCrop	Crops not elsewhere specified
OilCrop	Crops used primarily for production of oil
PalmFruit	Oil palm and coconuts
Rice	
Root_Tuber	Starchy root vegetables
SugarCrop	Sugar cane and sugar beets
Wheat	

2.1.1.1 Production and Harvested Area

Agricultural production and harvested area by region and crop are based on the FAO PRODSTAT database (FAO 2010). Production and harvested area in the 1990 model time period are calculated as the average from 1988 to 1992, and the data in the 2005 model time period are based on the average from 2003 to 2007. Within each region, production and harvested area in each time period are disaggregated to AEZ on the basis of AEZ-within-region production and harvested area shares in GTAP (2009). The mapping from countries to GCAM regions is shown in Table A1, and the mapping from FAO/GTAP crop categories to GCAM primary commodities is detailed in Table A2. Cotton harvested area and production is disaggregated to OilCrop and FiberCrop on the basis of the tonnage of cotton lint produced compared to total cotton mass. The only adjustment to the data is as follows: production of any crop within region and AEZ is adjusted such that if an AEZ accounts for less than 1.5% of total regional production of a given crop, its yield cannot exceed the maximum yield observed in USA for that crop in any AEZ. This step is designed to limit the effects of very high yields in the base year in AEZs with very low production—whether from small-scale highly managed plots with higher yields than would be observed if production were scaled up, or from anomalous data—which could generate unrealistically high land profit rates in certain sub-regional AEZs.

As a methodological note on the processing of the FAO data, FAO crop commodity production is generally indicated in market weight, i.e. the weight at the water content required for sale on the market (to be distinguished from dry weight). This convention is held in GCAM; no adjustments are made to the FAO crop weights. However, consistent with the USDA's accounting practices (USDA 2011a), fodder crops are treated as if they are represented in terms of dry weight in the FAO databases. The actual FAO accounting on fodder crops is not documented, and it is generally unclear whether the values in the database represent wet weights or dry weights. In the USA, the FAO clearly multiplied the USDA's alfalfa production by 4, in order to indicate the production in wet weight. Therefore in our processing we divide this estimate by 4, and are consistent with the

USDA's totals. However, this conversion does not seem to have been used for the FAO's data on fodder grass in the USA (though there is no single conversion factor linking the two data sources). Outside the USA, we don't know what accounting practices were used for the data presented in the FAO databases; as such, no adjustments to the FAO's fodder crop production are made, and it is assumed that the quantities refer to dry weight.

Note that in GCAM, yield and land use are indicated in terms of cropland, rather than harvested area. The translation from harvested area to cropland is made on the basis of incorporation of GIS-based land cover maps, described in Section 4.1.1. We read in an exogenous ―harvests-per-year" quantity for each agricultural production technology that allows one to calculate the harvested area of any technology.

2.1.1.2 Prices

Calibration year (2005) prices are read into GCAM for each crop in all regions. Given that all crops (except for FodderGrass) are currently assumed to participate in the global market, these calibration prices do not vary by region, and are calculated as average producer prices in the USA between 2001 and 2005 in the FAO PRICESTAT database (FAO 2010). For composite crops (e.g. MiscCrop), the average commodity price is calculated as the production-weighted average in the USA, across all FAO crops that are mapped to the given GCAM commodity. For fodder crops not included in the FAO PRICESTAT database, USDA prices are used for alfalfa (FodderHerb; USDA 2011b) and other hay (FodderGrass; Baker and Lutman 2008).

2.1.1.3 Costs

Technology competition in GCAM takes place on the basis of relative profit rates per unit of land area, calculated from each crop's yield, price, and cost. Therefore, in addition to the calibration parameters already described, each technology is assigned a non-land variable cost of production, which reflects the sum of a range of intermediate inputs not explicitly modeled, such as seed, chemicals, fertilizer, fuel, and labor. Costs are based on the USDA estimates for various subregions of the USA for seven crops (wheat, corn, rice, barley, cotton, sugarbeet, and soybeans). Barley is used as a proxy for OtherGrain, sugarbeets are used as a proxy for SugarCrop, and soybeans are used as a proxy for OilCrop. In general, the mapping from USDA subregions to GTAP / GCAM AEZs is as shown in Table 2.2. Costs in AEZs not covered for any particular commodity are interpolated or extrapolated from costs in AEZs that do have estimates, and costs of producing commodities other than the seven listed are calculated as the costs of producing corn multiplied by the price ratio between the given commodity and corn. All costs are indicated per unit of crop produced. In GCAM 3.0, costs by commodity and AEZ are applied equally in all global regions, and do not change over time.

Table 2.2. Mapping from USDA subregions to AEZs in the USA region.

Subregion	AEZ
Ark Non-Delta	AEZ12
Basin and Range	AEZ07
California	AEZ09

Eastern Uplands	AEZ11
Fruitful Rim	AEZ12
Great Plains	AEZ07
Gulf Coast	AEZ12
Heartland	AEZ10
Mississippi Portal	AEZ11
Mississippi River Delta	AEZ12
Northern Crescent	AEZ10
Northern Great Plains	AEZ08
Prairie Gateway	AEZ07
Red River Valley	AEZ08
Southern Seaboard	AEZ12

2.1.1.4 Productivity Change

Agricultural productivity change is aggregated by GCAM region and commodity from an internal FAO database used in support of Bruinsma (2009), which has 108 countries and 34 commodities. We aggregate the data for irrigated, rainfed, and total agricultural production, harvested area, and yields, but at present we only use the total. The projection years are 2005 (base year), 2030, and 2050, which allows annual productivity change rates to be calculated for each region and crop. These projections are not downscaled to AEZs, and at present there is no effort to differentiate yield improvements by AEZ within region. In the future this could be worth investigating. At present, the core model applies the median improvement rate across all crops within each region to each crop, rather than using the crop-specific yield improvements described above. This is done in order to minimize the economic distortions of differentiated yield (and therefore profit) increases. The same rate is applied to biomass as to other crops.

2.1.1.5 Residue biomass

Residue biomass parameters consist of a harvest index (mass of crop harvested divided by total above-ground plant biomass), root to shoot ratio, the plant water content, and a parameter specifying a certain amount of plant biomass that can not be harvested, for purposes of erosion control. Data used are shown in Table A.5, and the data sources used for these parameters are shown for each FAO crop in Table A.6. These values are used to generate weighted averages specific to each region and primary commodity. However, note that for single-crop GCAM commodities (e.g. rice), the same value is used in all regions. For composite crops, such as MiscCrop, the residue biomass parameters in any region will be the production-weighted averages of all of crops that are mapped to MiscCrop.

2.1.2 Forest Products

Forest products in GCAM consist of total roundwood in FAO's FORESTAT database (FAO 2010), which is equal to the sum of industrial roundwood and fuelwood. No distinction is made between these two types of wood in GCAM. Production and net exports are used directly from the FAO database, with a slight adjustment to net exports to ensure that the global sum is zero. Forest product calibrated prices are based on FAO’s export prices in the USA from 2001 to 2005, and costs of production are based on Arriagada et al. (2006).

Forest-related residue biomass production consists of forestry residues—the residues from logging operations—as well as milling residues. Because forestry flows are tracked in volume (billion cubic meters), the quantities available for use for residue biomass are converted to mass. The core scenario assumes an average wood density of 500 kg per cubic meter of wood, a harvest index of 0.8 (Commonwealth of Australia 1999), and an erosion control quantity of 0.2 kg per square meter (Pannkuk and Robichaud 2003).

The assignment of roundwood production to land is described in Section 4.1.4.

2.1.3 Pasture

Pasture output is defined as dry-weight equivalent of the grass consumed by animals involved in animal commodity production that is not tracked in FAO’s data on harvested area and production of grass. This quantity does not reflect the total grass production in pastures in the given region/AEZ, but rather only the grass that is consumed by animals involved in animal commodity production. The calibrated price is equal to the price of hay in the USA, and is assumed equal in all regions. No variable cost is used for pasture.

The assignment of pasture grass production to AEZs within a given region is described in detail in Section 4.1.5.

2.1.4 Purpose-grown biomass

Purpose-grown biomass is not part of the calibrated input set, and as such needs to be assigned characteristics allowing the model to perform a ―ghost” calibration (discussed in Wise and Calvin 2011). In this section, we describe our current approach to modeling biomass production and use. This approach takes full advantage of our developments in modeling agriculture and land use at the subregional AEZ level across the world. This new structure allows us to model biomass crop yields specific to each individual AEZ within each of the 14 GCAM regions. In addition, biomass crops compete with food and other crops with yields that are also specific to these subregional AEZs rather than national or regional averages that may gloss over subregional differences. Finally, this approach allows for multiple biomass crops around the world and within the AEZs. For example, an AEZ might be suitable for both a perennial crop such as switchgrass and a woody plant like willow.

In general, the GCAM model is an internally consistent modeling structure for analyzing the energy and agriculture systems in an integrated manner. Its main function is not as a repository of data. However, it does need explicit data to operate, and explicit numerical assumptions are necessary. In that spirit, Table 2.3 shows current biomass crops we have parameterized for the GCAM model. In general, we have chosen crops that are representative for those that can be grown advantageously in different parts of the world. These choices do not imply that other similar crops would not also be grown, and these crops and modeling results should be interpreted as being representative of similar crops as well.

Table 2.3: Yields and Costs for Dedicated Bioenergy Crops[1]

		Average Crop Yield ($kg/m^2/yr$)	**Energy Content (MJ/kg)**	**Energy Yield (MJ/m^2)**	**Cost ($2008/GJ)**
Switchgrass	Most regions				
Miscanthus	Western Europe	1	16	16	3.5
Willow	Eastern Europe	1	19	19	2.3
	Western Europe	1	19	19	2.3
	China	1	19	19	2.3
	USA	1	19	19	2.3
Eucalyptus	Africa	1.2	19.4	23	2.4
	Latin America	1.2	19.4	23	2.4
Jatropha (oil)	Africa	0.14	40	5.6	4.2
	India	0.14	40	5.6	4.2

Several dedicated bioenergy crops have been included, beyond the generic switchgrass crop that has historically been used in GCAM. For perennial crops, the GCAM continues to use switchgrass in most regions, with the option for miscanthus production in Western Europe. Miscanthus yields shown here are for the near term, but it has the potential to have much higher yields than switchgrass in the longer term (potentially 2 kg/m^2), at a significantly higher cost. Commercial experience with miscanthus is limited (Faaij 2006).

Willow is a potential perennial woody bioenergy crop in Eastern and Western Europe, as well as some regions of China (Xiong et al. 2008) and the United States. It is a short-rotation coppice crop, with yields typically higher than other crops, but it can only be harvested every 3-4 years. Willow would be best suited for cold, wet climates, and is already used to some extent in European countries such as Sweden and the U.K.(Faaij 2006). Poplar is another common woody biomass crop, frequently grown for pulp production, but was not considered in this analysis due to its many similarities with willow. In warmer, more tropical climates, Eucalyptus is often the favored crop. 6 Mha of Eucalyptus plantations currently exist in Brazil, primarily for charcoal production for iron smelting (Hamelinck et al. 2005). In addition to Latin America, there is also potential for Eucalyptus in Africa (Batidzirai et al. 2006). Tree stems are harvested throughout the year, while leaves and small branches are generally left on the field.

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[1] Jatropha has a secondary output of 2.2 $MJ_{cellulose}/MJ_{oil}$, assuming 50% of seedcake left on field. Sources for crop yields include: (Faaij 2006; de Wit and Faaij 2010) for Willow & Miscanthus, (Hamelinck et al. 2005) for Eucalyptus, (Openshaw 2000) for Jatropha, and (Thomson et al. 2009) for Switchgrass

Jatropha can be used specifically for the production of biodiesel, and (in the GCAM) can be grown in the marginal lands of India and Africa. Oil from Jatropha, as well as other conventional oil crops, does not undergo the pelletization process instead a standardized transesterification process is employed to convert the oil to biodiesel.

While average yields are readily available from the literature for these crops, it can be a challenge to scale these yields appropriately for the different conditions in each of the 18 AEZs. For food and other crops that are currently grown, current crop yields are readily computed for each subregional AEZ from historical production and land use areas. As long as crops are grown at a meaningful scale within each subregional AEZ, these yields can be interpreted as representative yields for that AEZ. (For example, we would want to avoid using very high yields on very small land areas where intensive management was applied. However, these situations are exceptions to the data.)

For biomass energy that comes from existing food crops that have historical production data by subregional AEZ, the existing yields are already well-established by the data. In contrast, new biomass crops have not typically been grown at large scale or over economically substantial land areas, and especially not all over the world. As a consequence, we need to rely on the research literature and other modeling for representative future yields of new biomass crops.

The introduction of new biomass crops in GCAM in regions outside the U.S. presents additional challenges. The yields found in literature may not be appropriate for other regions of the world due to differences in agriculture management practices or perhaps physical conditions that are not captured by the AEZ categories. The new biomass crops must compete in an unbiased manner with historical crops that are part of the calibrated base year data. In developing regions where current yields of food crops are relatively low, adding a U.S.-based yield for a new biomass crop may make biomass look like a high-yielding super crop compared to the existing food crops. In this case, biomass crops may dominate in these regions, but this domination may be an artificial result. On the other extreme, there may be AEZs in other regions where conditions would result in higher yields than the U.S.

The current GCAM approach to parameterizing international biomass yields is to index them to their base year yields of wheat and grains relative to the U.S. yields of wheat and grains in corresponding AEZs and apply the AEZ granularity to these indexes. For example, if the yield of wheat in AEZ 7 in Africa is half the U.S. yield, then the current biomass yield in AEZ 7 in Africa would be set to half the biomass yield in U.S. AEZ 7. For future model periods, the African biomass yield could catch up to the U.S. if a higher rate of agricultural productivity improvement is assumed, which is typical for developing regions. Again, other approaches and assumptions about future biomass yields are clearly possible. In this example, a developed region could buy land in Africa and apply modern intensive management practices to achieve a higher biomass yield. Of course, they could theoretically also do that with food crops, which would affect the competitiveness of biomass. GCAM provides a platform for exploring alternative assumptions and scenarios of biomass and other yields around the world.

2.2 Secondary (Animal) Commodities

Animal commodity production is modeled in detail for the following five animal commodities: beef, dairy, pork, poultry, and sheep & goat. A sixth category for animal products whose production is not explicitly modeled is included (other meat and fish). Mapping from the FAO animal categories to these GCAM commodities is shown in Table A4. Production of each animal type is represented with a range of production technologies characterized by different types of systems (pastoral or mixed), and different types of feed inputs (grass, non-grass fodder crops, feedcrops, or scavenging and other). This representation is detailed further in Section 3.1.3.

Unlike agricultural production technologies, animal production technologies are input at the level of the GCAM region, with no direct link from animal production to subregional AEZs. Each technology is characterized by a feed input-output coefficient (feed input per unit of animal output), and a non-feed cost that accounts for the remainder of the costs of animal production. The input-output coefficient for fodder crops and grass is indicated in dry feed equivalent (e.g., tons of dry grass per ton of beef produced), and is from IMAGE 2.4 (documented in Bouwman et al. 2006). The non-feed cost, assumed equal for all regions, is calculated to return approximate producer prices for the different animal products in the USA in the 2005 model time period.

At present, GCAM does not allow trade of secondary goods, but a number of regions have high shares of either imports or exports in the base year data. In order to retain consistency with the data on both production and consumption, we therefore implement either a fixed export or import quantity in each region, depending on whether the region is a net importer or exporter. The quantity of net exports in the 2005 model time period is assumed constant through the end of the century.

3 Disposition of Commodities

3.1 Disposition of Primary Commodities

Primary commodities in any GCAM region are partitioned among the following five dispositions: net exports, consumption as food by humans, animal feed, biofuel production, and other uses. These five dispositions must balance in two ways: (1) for any region/commodity, the sum of all dispositions must equal the production; and (2) the global sum of net exports of each crop must be zero.

The main data source used for this partitioning is the FAO Commodity Balances (FAO 2010), which include flows of primary plant-based commodities, secondary animal commodities, and secondary plant-based commodities (e.g. vegetable oils). The production of secondary plant-based commodities is not explicitly modeled in GCAM; instead, the flows of these goods are mapped to the primary commodities from which they were produced (e.g., corn oil is mapped to corn), and any processing losses will be accounted as other net uses. Note that this system works well for handling processing losses, but would not do as well with processing gains. This is one reason why alcoholic beverages are not included at present[2]; if future users wish to include this, they will need to ensure that the processing gains (from the weight of added water in the final product) do not throw off the commodity mass balances.

3.1.1 Net Exports

With the exception of fodder grass (hay) and pasture grass, all primary commodities are assumed to participate in global markets. Trade in global markets is tracked in GCAM only in terms of net exports; the base year flows are calibrated to FAO's Commodity Balances, with slight adjustments to guarantee that global net trade is zero, and to ensure that no regions have negative ―other uses.” This latter step is described in Section 3.1.5. Note that in the GCAM model input set, net exports are not read in for primary commodities, but rather can be calculated as the production minus the sum of all tracked uses.

3.1.2 Food

Consumption of primary agricultural commodities by humans is indicated both in terms of weight (Mt/yr) and calories (Pcal/yr); caloric contents of FAO's primary and secondary commodities are shown in Tables A3 and A4, respectively. The food final demand in GCAM, shown in Figure 3.1, is indicated in calories, by applying a region-specific caloric conversion factor to each commodity. The weighted average caloric content of each primary commodity is calculated based on the caloric contents of the individual components to the GCAM commodity classes. Note that this calculation may apply to single-crop commodities (e.g. Corn, Rice) as well as the composite commodities (e.g. MiscCrop), as even some single-crop commodities may nevertheless be used in producing secondary plant-based goods. For example, the weighted average caloric content of ―Corn” in each region will be equal to the share of primary corn consumed by humans as opposed to the consumption of corn oil, multiplied by the caloric contents of each of these components.

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[2] The main purpose of separating ―food” and ―nonfood” uses is to represent the consumer diet in each region; while the decision of whether to include alcoholic beverages in the consumer diet is debatable, in general the FAO excludes it. Note that modeling of alcoholic beverages would also require specifying a primary commodity (or allocating production to several commodities assuming certain shares), which is not available from the FAO data.

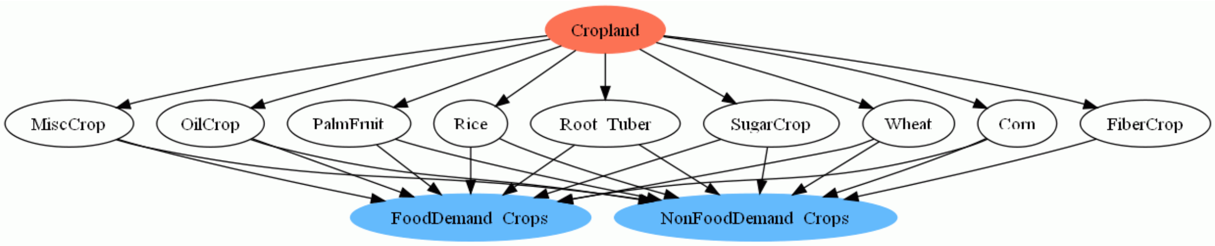

Figure 3.1: Current GCAM Food crop categories.

3.1.3 Feed

The use of crops as feed in GCAM is explicitly modeled, with specific animal production technologies that require different amounts of feed per unit of output. Production technologies are included for five animal commodities (beef, dairy, pork, poultry, and sheep&goat); a catch-all sixth animal commodity (Other meat & fish) is handled in aggregate form. The full representation of secondary commodity production, including all inputs, is shown in Figure 3.2. The characterizations of animal production technologies are based on IMAGE 2.4 data; subsectors are –mixed” and –pastoral”, and inputs to the systems are (1) fodder herbs and crop residues; (2) pasture and foddergrass; (3) feedcrops; and (4) scavenging & other. All but scavenging & other are further disaggregated, and described in detail below.

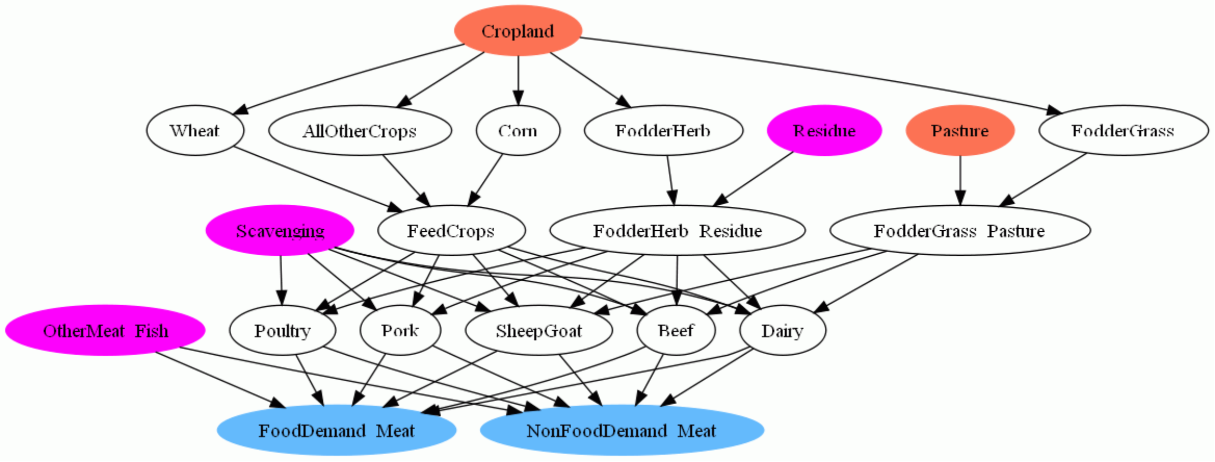

Figure 3.2: Current GCAM Meat Categories and Inputs

Note that the characteristics of animal production technologies are taken from the IMAGE 2.4 data, whereas animal commodity production, fodder crop production, and the use of crops as feed are available from the FAO data. At present, we use the FAO animal commodity production, disaggregated to production technologies according to the shares in the IMAGE 2.4 data, and we also use the feed input-output coefficients from IMAGE 2.4. This yields a bottom-up estimate of the regional demand of the four different types of animal feed that will be different from the top-down FAO data on fodder crop production, and the use of crops as feed. The following sections describe how the discrepancies between this bottom-up calculation and the top-down supply data from the FAO are handled.

3.1.3.1 Fodder herbs and residue

Non-grass fodder crops (―FodderHerb”) in the FAO (2010) queries include mostly corn silage (while this is technically a grass, IMAGE counts it as a non-grass fodder crop), alfalfa, and unspecified legumes used as animal feed. In each region, residue demand is calculated as the discrepancy between fodder herb production (from FAO 2010) minus fodderherb+residue demand (bottom-up estimate). FodderHerb is modeled as a global market in GCAM. In time periods where global production exceeds global demand of fodderherb+residue, the extra FodderHerb production is mapped to ―other uses.” In the current input set, in the 2005 time period there is excess demand, so this is produced by a global resource called ―Residue.” The production of this residual quantity is allocated amongst regions with excess demand according to the magnitude of these demands. This residue resource is not linked to the crop module, and is parameterized such that it can not expand beyond its base year levels in the future.

3.1.3.2 Pasture and foddergrass

Pasture output in each region—grass consumed in pastures—is calculated as the discrepancy between FAO’s FodderGrass production and the total grass demand from the bottom-up feed demand calculations. This creates some complications in regions that have high derived demand for grass relative to indigenous production of FodderGrass, and relative to the amount of pasture land in the region. In several regions with very low production of FodderGrass and small amounts of land that is in pasture (Japan and Korea), we have adjusted the IMAGE-based animal production technology shares in order to reduce the grass inputs; note that this reduction is consistent with more detailed literature (Kim 1995).

3.1.3.3 Feedcrops

The proportional allocation of feedcrop production to specific crop types in each region follows the FAO (2010) Commodity Balances estimates, with the quantity of each crop used as feed scaled such that the regional totals match the bottom-up derived demands of feedcrops. That is, the bottom-up derivation (based on IMAGE 2.4 animal production data) is given precedence here, and the allocation of crops to feed is adjusted from the FAO’s data. This discrepancy (GCAM feed vs. FAO feed) will be balanced by an effective adjustment to each region’s other (non-food) uses of the crop.

3.1.3.4 Scavenging and Other

This input to animal production basically consists of items that are not primary agricultural products, nor marketed by-products from the processing of primary agricultural products. It includes garbage and other waste, by-products from animal commodity production, and a range of other unmarketed items that are nevertheless quite important for animal production in certain regions, notably India. This is modeled as a resource that can not expand in deployment relative to its base year allocation.

3.1.4 Biofuels

GCAM includes several biomass liquids refining technologies that link the energy and agricultural systems, including technologies for cellulosic or Fischer-Tropsch liquids production from bioenergy crops or crop residues, as well as several conventional technologies that use primary agricultural commodities. The former technologies are not in the base year input set, and are not documented further here (but see Luckow et al. 2010 for a review). However, the use of primary agricultural commodities for biofuel production is of particular importance for near term modeling of agricultural markets. Biofuel production from primary agricultural commodities is not disaggregated from generic ―industrial use” in the FAO Commodity Balances, so the calibration is based on additional research, documented in this section.

GCAM calibrates to existing, first-generation biofuels production, including corn ethanol and soybean biodiesel in the United States, as well as ethanol from sugarcane and sugar beets in Latin America and Western Europe, respectively. We note here that this marks a departure from previous versions of GCAM; while our previous focus on cellulosic ethanol was acceptable given the model’s long-term focus, the addition of these technologies gives us better understanding of short-term dynamics. Today, there is no (or very little) cellulosic ethanol production, but significant levels of ethanol from corn and sugar. In 2009 U.S. ethanol refineries used 3.8 billion bushels of corn (or 30% of gross corn use) to generate 10.6 billion gallons of ethanol ("2010 Ethanol Industry Outlook" 2010).

Inputs and costs to these first-generation technologies are summarized in Table 3.1, and compared to the advanced (second-generation) alternatives. To produce a gallon of corn ethanol, it takes 0.36 bushes of corn kernels, 0.6 kWh of electricity, and 0.024 MMBtu of natural gas. On a per GJ of product basis, this works out to 112 kg of corn, 0.026 GJ of electricity and 0.32 GJ of natural gas. At present, we do not consider the secondary output of distillers grains, but in practice this would be easy to implement. To be consistent with Perrin et al. (2009), the coefficient would be of 30 kg of animal feed per GJ of ethanol (or 14.8 lbs DM/bu). Note that consideration of this secondary output in model base years would require re-calibration of feedcrop production.

Non-energy costs are the sum of capital costs, enzymes, labor, maintenance, denaturant (to make it undrinkable), and miscellaneous other expenses, and amount to 7.67 $2008/GJ (Perrin et al. 2009). This is coincidentally about the same as the cellulosic ethanol cost of 7.64 $2008/GJ, but it is important to note that cellulosic ethanol does not become an option until 2020.

To properly calibrate the model, the 0.33 EJ of ethanol in the US than was previously mapped to cellulosic ethanol in 2005 was remapped to corn ethanol, and the required natural gas and electricity inputs were subtracted from industrial energy use. The corn inputs are subtracted from the corn non-food demand.

In Brazil, sugarcane is use to produce large volumes of ethanol every year. Sugar is distinct from corn in that it does not require addition energy inputs for ethanol production. The cane is crushed to extract the juice, and the remainder (bagasse) is used for process fuel (the residue GCAM generates from sugar is different from bagasse; it represents sugarcane tops, leaves and immature parts of the stem that are left in the field at harvest). To produce a gallon of ethanol from sugarcane, it takes 47 kg of sugar, or about 580 kg of sugarcane per GJ of fuel (Outlaw et al. 2007). Capital and processing costs are marginally higher than corn, due to the larger volumes involved, with a total non-energy cost amounting to between 9.18 $2008/GJ (Shapouri et al. 2006; Outlaw et al. 2007). Sugar beets are used similarly in Western Europe for ethanol production, although the processing costs are substantially higher, leading to a total cost of about 28 $2008/GJ.

There is a large disparity in reported feedstock costs for sugarcane ethanol. Outlaw et al use $17/ton sugarcane (in 2005$), while Coelho (2005) uses 11.4 $/tonne. 2010 U.S. national average sugarcane prices are approaching $35/ton, though this is a substantial jump from 2005, when prices were closer to $28/ton ("USDA Economic Research Service" 2010). Prices in Brazil were much lower, closer to $23/ton ("Brazil Sugar Annual Report 2009" 2009). The higher relative feedstock cost in GCAM (about $40/tonne) made sugarcane ethanol entirely unprofitable in the early half of the century, in the absence of a policy.

The 0.17 EJ and 0.024 EJ of ethanol in 2005 in Latin American and Western Europe, respectively, are now mapped to ethanol from sugar in GCAM.

Table 3.1: Summary of GCAM Refining Technologies, inputs per GJ of refined liquid output[3]

	Crop Input (kg)	Dedicated Bioenergy Input (GJ)	Natural Gas (GJ)	Electricity (GJ)	Cost (2008$/GJ)
Corn Ethanol	112	-	0.32	0.03	7.67
Sugar Ethanol	582	-	-	-	9.18
Soybean Biodiesel	146	-	0.03	-	2.51
Fischer-Tropsch	-	1.96	-	-	8.88

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[3] Costs do not include feedstock cost. An additional cost markup of $3.50/GJ is added between the refining sector and the transportation sector. Sources: (Perrin et al. 2009) for corn ethanol, (Shapouri et al. 2006; Outlaw et al. 2007) for sugar ethanol, (Pimentel and Patzek 2005; van Kasteren and Nisworo 2007) for soybean, (Aden 2008) for cellulosic ethanol, and (van Vliet et al. 2009) for Fischer-Tropsch

Cellulosic	-	2.06	-	-	7.64

For crops that produce oil directly, such as soybeans and palm fruit, there is now a distinct low-cost refining option. We assume an oil content of 18% for soybeans, and 20% for palm fruit (Pimental and Patzek 2005, Thoenes, 2006). The transesterification technology also applies to Jatropha. There are several potential options for the transesterification process to employ, using different combinations of catalysts, and elevated temperature and pressure. In this case we model a continuous-process transesterification reaction catalyzed by sodium methoxide at about 60ºC. (Haas et al. 2006). For every GJ of biodiesel produced, 1.03 GJ of bio-oil are consumed, as well as 0.03 GJ of natural gas. The technology cost is low, \$2.51/GJ compared to \$7.67/GJ for corn ethanol, but crop prices are generally much higher for these crops.

3.1.5 Other Uses

Other uses, referred to in GCAM as ―NonFoodDemand,” consist of any remaining uses of agricultural commodities; these include the following categories in the FAO Commodity Balances: industrial processing, waste, seed, stock changes, and ―other util.” At present this category is also used to track processing losses from the production of secondary plant-based items with higher calorie densities than the primary commodities from which they were produced, such as vegetable oils, as described in Section 3.1.2.

In practice, other uses are simply calculated in each region as the production minus all other tracked dispositions. Without any adjustment to any of the aforementioned dispositions, this calculation can yield negative estimates, which may be due to stock additions, higher amounts of feedcrop use than was in the FAO's estimates, or simply statistical discrepancies. In region/commodities where other net uses are negative, we set the category to zero, and increase net exports in order to preserve the within-region balance. This requires an increase in all other regions' net exports (so that the global sum remains equal to zero), which in turn is balanced by a decrease in all other regions' ―other uses.” These adjustments are assigned to other regions according to each region's share of the global total of other uses of the crop. The result of these adjustments are that (1) the global sum of net exports still adds to zero; (2) in any region, production minus net exports is still equal to the sum of all demands; and (3) production and explicitly modeled uses—food, feed, and bioenergy—are unaffected by these adjustments.

3.2 Disposition of Secondary (Animal) Commodities

The dispositions available for animal commodities include net exports, food, and other uses (i.e., no feed or biofuels). The mapping of FAO's animal commodities in the Commodity Balances to GCAM's secondary commodities is shown in Table A4. Meat production, net exports, food consumption, and ―other uses” are not adjusted from the data in the FAO (2010) Commodity Balances, except to ensure that global net exports sum to zero, and the sum of consumption and net exports is equal to the production within any region. As with agricultural commodities, the net exports and other uses (i.e., ―NonFoodDemand”) are adjusted to ensure consistency, with no adjustments made to the production and food consumption. Because GCAM is not currently set up to model trade of secondary products, the exports in net exporting regions are modeled as a final demand that remains fixed over time, and imports in net importing regions are modeled as a third subsector of meat production (i.e. mixed, pastoral, and imports) with a single fixedOutput technology that does not consume any feed. The levels of imports and exports are set equal to their 2005 levels through 2095. In this way, the global sum of imports and exports is always zero, and the levels remain fixed at their levels in our 2005 model time period.

3.3 Final Demands of Commodities

The final demands relevant for the agricultural and land use component include the following categories: food demands of crops, food demands of animal products, non-food demands of crops, animal products, and forest products. Each of these final demands is represented with a per-capita-based demand function, whereby demands increase linearly with population, and are affected by price and per-capita GDP according to exogenous assumptions of income and price elasticity. These assumptions, as well as the structure of the inputs to the final demands, are detailed in the following sections.

3.3.1 Food Demand: Crops

Although the demand function structure will allow greater flexibility, we have parameterized the per capita modeling of demand for food crops to be fairly rigid. First, we have assigned zero price elasticities to the demand function for food crop consumption, meaning food crop demands must be met regardless of future prices. Also, we have assigned a zero value to the logit sharing exponent that determines the mix of individual food crops that compete to provide total food crop demand, which essentially fixes food crop shares to base year values within each region (see Figure 3.1). This was done for in order to be conservative, as the consumer diet is not structurally modeled in GCAM at this time. This approach preserves regional diet preferences; further, the approach avoids the potential model result of shifts in the diet that may be unsustainable, e.g. a shift to a sugar diet.

We have set the income elasticities of food crop demand to 2050 so that the model output with the reference GDP path matches the FAO's (2006) projections in seven global regions, in terms of kcal per person per day. The FAO's regions include the following: industrial countries, transition countries, East Asia, South Asia, Latin America and the Caribbean, sub-Saharan Africa, and Near East / North Africa. These elasticities assumed are therefore most appropriate for the reference case income growth path and might need to be changed for other paths. Note that no effort is made to include FAO's projected shifts between different crop types in the six global regions.

3.3.2 Food Demands: Meat

Meat demand is modeled much like food crop demands in that the same form of GCAM per capita demand function is used. As with food crop demands, the shares of types of meat in each region is fixed at base year shares in each region, though this could be altered (see Figure 3.2). Again, this fixing reflects preservation of regional diet preferences to historical data, though these could be changed for future scenarios by changing the parameters either to different fixed values or by allowing economic switching. Also, as with food crops, income elasticities are assigned so that per-capita meat consumption from 2005 to 2050 matches the growth rates in the FAO (2006) projections. They are also tied to the reference case economic growth path.

Differently from food crop demand, the price elasticities for meat have not been set to zero. That is, the data assumes that meat demand responds to changes in price, and meat demand will go down as its price goes up, all else equal. Price elasticities are generally set to -0.25, with a low value of -0.09 used in the USA, consistent with USDA (2011c).

3.3.2.1 Other Meat and Fish

In order to represent the full consumer diet in each region, a demand category had to be constructed for fish, game, and other sources of meat whose production is not modeled in detail. This category is one of the components of meat demand in each region, with its share fixed in each region to base year data just as with the rest of the meat demand categories.

3.4 Non-Food Demands for Crops, Meat, and Forest Products

Non-food demands for crops and meat products include a wide variety of uses including clothing, soap, and many other products, and in GCAM these demands also include stock changes, seed, processing losses, waste, and anything else not already described. It is necessary to include these demands in the model for purposes of mass balancing, but the demands themselves are not modeled in detail. There are three non-food demands represented: crops, meat, and forest products (note the for forest products, this includes the entirety of the demands). The demands are modeled using simple per capita demand functions, with zero price and income elasticities; as such, the future demands scale directly with population in each region. While the demand for forest products is a single commodity in GCAM (total roundwood), the crop and meat demands are characterized by a blend of component commodities whose relative shares are fixed to base year values in each region. Because these categories are so broad, the conservative approach to not letting the model change shares was used.

However, this approach makes these demands just as sticky as food demands, and care should be taken to see that they are not dominating results inappropriately in modeling scenarios. Some amount of switching or price elasticity may be considered in the future. Also, note that these do not include energy demands since these are modeled explicitly in the energy sectors of GCAM.

4 Land Use

The final portion of this document provides an overview of the land types used, and the data sources and assumptions for all parameters relevant for the representation of land use. These include the base-year and historical land allocation, average carbon contents, land values, and logit exponents assumed.

4.1 Land Allocation

In general, the source data used is spatial maps from HYDE (Goldewijk and Ramankutty 2004) for cropland, pasture, and built-up land, and SAGE potential vegetation (Ramankutty and Foley 1999) for all remaining lands. The mapping from the land use types in these two databases to GCAM land use types is shown in Table 4.1. As shown, the SAGE categorizations are only used in lands considered ―Unmanaged" in the HYDE database; otherwise, the HYDE categorization takes precedence.

Table 4.1. Mapping from GIS land types (SAGE, HYDE) to GCAM land types.

SAGE land type	HYDE land type	GCAM land type
Tropical Evergreen Forest/Woodland	Unmanaged	Forest (managed and unmanaged)
Tropical Deciduous Forest/Woodland	Unmanaged	Forest (managed and unmanaged)
Temperate Broadleaf Evergreen Forest/Woodland	Unmanaged	Forest (managed and unmanaged)
Temperate Needleleaf Evergreen Forest/Woodland	Unmanaged	Forest (managed and unmanaged)
Temperate Deciduous Forest/Woodland	Unmanaged	Forest (managed and unmanaged)
Boreal Evergreen Forest/Woodland	Unmanaged	Forest (managed and unmanaged)
Boreal Deciduous Forest/Woodland	Unmanaged	Forest (managed and unmanaged)
Evergreen/Deciduous Mixed Forest/Woodland	Unmanaged	Forest (managed and unmanaged)
Savanna	Unmanaged	Grassland
Grassland/Steppe	Unmanaged	Grassland
Dense Shrubland	Unmanaged	Shrubland
Open Shrubland	Unmanaged	Shrubland
Tundra	Unmanaged	Tundra
Desert	Unmanaged	RockIceDesert
Polar Desert/Rock/Ice	Unmanaged	RockIceDesert
[ALL]	Pasture	Pasture (managed and unmanaged)
[ALL]	Built-up land	Cropland
[ALL]	Cropland	Urbanland

4.1.1 Cropland

Cropland is based on data from HYDE (Goldewijk and Ramankutty 2004), but is expanded as needed in sub-regional AEZs with anomalously high harvested areas in relation to cropland; this method is described here. First, the total cropland available for harvest in a representative year is calculated as the HYDE cropland minus the known fallow land in each region. Fallow land is calculated for each region as either (a) Fallow Land divided by the Total Arable Land, or (b) the Total Arable Land minus Temporary crops, divided by Total Arable Land. These queries are in the FAO (2010) RESOURCESTAT database. While these three queries are not available for many countries in the FAO dataset, each of the 14 current GCAM regions had at least one country that had enough data to do an estimate using either (a) or (b). For those with all three queries available, the estimates derived by either method were reasonably close, and method (a) was used. This was used as the portion of cropland that is fallow in any given year. The same fraction was assumed in 1990 and in 2005, and in all AEZs. This fallow land is printed for each region in Table 4.2 and is a component to GCAM's ―Other Arable Land" category.

Table 4.2: Portion of each GCAM region's cropland that is fallow. Source: FAO RESOURCESTAT.

Region	Fallow Cropland (%)
USA	9.2%
Canada	8.8%
Western Europe	13.0%
Japan	14.5%
Australia_NZ	48.3%
Former Soviet Union	7.2%
China	16.5%
Middle East	25.7%
Africa	18.4%
Latin America	38.1%
Southeast Asia	21.9%
Eastern Europe	9.4%
Korea	2.4%
India	28.3%

The regional harvested-to-cropped ratio is then calculated as the sum of harvested area of all crops divided by the cropland considered to be in production (i.e., not fallow), in 1990 and 2005, for each region. The following rules are then applied: In regions where the harvested:cropped ratio is less than 1, it is assumed that all crops have a harvested:cropped ratio of 1, and the resulting discrepancy in cropland is added to ―Other Arable Land." In regions where the harvested:cropped ratio exceeds 2.5, the harvested:cropped ratio is set to 2.5, and land is re-allocated from all unmanaged uses (that is, grassland, shrubland, unmanaged forest, and unmanaged pasture) into cropland. This assumption of a maximum harvested:cropped ratio of 2.5 is intended to be consistent with Monfreda et al. (2008)'s assumption of a physical limit of 3 harvests per year. The Monfreda et al. (2008) estimate, referenced to Dalrymple (1971), is made at the county level (note: *county*, not country), whereas our assumption applies to entire AEZs within GCAM regions. In sub-regional AEZs where the harvested:cropped ratio exceeds 1, no further cropland is added to ―Other Arable Land." The final adjustment to croplands is to expand croplands in AEZs where the production of any crop is less than 1.5% of the total regional production of the crop, and its ―economic yield" (production per unit of cropland) exceeds an assumed maximum yield for the crop, which for most crops is based on the USA data. This is a repeat of the adjustment applied to the production earlier, but it differs here in that (a) it is based on economic, not agronomic, yields, and (b) the means of reducing yields is not to cut production but rather to expand cropland.

The cropland allocated to each crop is then calculated on the basis of harvested area; since all crops within any region/AEZ are assumed to have the same harvested:cropped ratio, this calculation is simple. Again, other arable land consists of the sum of the fallow land from the FAO data, and any cropland from the Hyde data that is in excess of harvested area from the FAO.

4.1.2 Urban Land

Historical urban land (built-up land) is compiled from HYDE, with no adjustments.

4.1.3 Tundra, Rock/Ice/Desert

These categories are simply compiled from the SAGE data, with any of the HYDE managed land deductions as necessary. No further adjustments are made.

4.1.4 Managed Forest

Managed forest land is calculated in each time period based on each region’s annual roundwood production, disaggregated to AEZs according to the estimated forest biomass production of each AEZ. Forest biomass production is calculated as the assumed vegetation carbon content of the given AEZ (see Section 4.2.1), divided by 0.45 to convert to vegetation biomass, then divided by the assumed ―mature age,” which is used as a proxy for the rotation period. Biomass is converted to forestry yields (cubic meters of wood per square meter per year) assuming a global average wood carbon density of 288 $kgC.m^{-3}$ (based on Ketterings et al. 2001).

This method is functionally equivalent to calculating ―managed” forest land as the logging rate (thousand km^2 clearcut each year) multiplied by the recovery period (years); in this way the ―managed” forest represents not only what was cut in a given year, but all forests that would be necessary to sustain the given annual logging rate. As such, the method implicitly assumes that the logging rate in the model base periods is in fact less than the total annual biomass production in all forests of any region; with the current regional designations and calculations of forest biomass production, this is borne out in the data. Table 4.3 indicates the portion of each region’s forests that are considered to be managed.

Table 4.3: Portion of each GCAM region’s forests that are considered “managed” for timber production.

GCAM region	Managed forests (%)
USA	17%
Canada	6%
Western Europe	27%
Japan	7%
Australia_NZ	18%
Former Soviet Union	4%
China	18%
Middle East	20%
Africa	9%
Latin America	3%
Southeast Asia	7%
Eastern Europe	22%
Korea	9%
India	34%

4.1.5 Managed Pasture

Managed pasture land allocation is calculated in similar fashion as managed forest; total regional production is derived from the Pasture feed inputs to animal production systems (as described above), and this is disaggregated to AEZs on the basis of the estimated biomass production of each region/AEZ. Pasture biomass production is calculated for each AEZ on the basis of global average yields by AEZ for all crops mapped to ―FodderGrass.” The total grass production in pastures of each region is calculated as the sum of each AEZ’s yield multiplied by land area.

As a first estimate, the portion of each region’s pasture that is considered ―managed” is calculated as the pasture-derived grass inputs to animal production systems (total grass minus FodderGrass, or hay, production), divided by the total grass production on all land designated as pastures. However we assume that only as much as 85% of the total pasture land in any region can be assigned as ―managed.” In regions where pasture-derived grass inputs to animal production exceed 85% of the total regional pasture biomass production, we simply allow a higher yield on the managed pasture. The alternatives would have been to (a) expand pasture lands, or (b) change the animal production data to reduce grass consumption. The former option was not done in order to minimize the post-hoc adjustments to the SAGE/HYDE land cover estimates. In the current data set, the latter option was used in several instances where additional research indicated that the IMAGE-based animal production data likely had unrealistically high input shares allocated to grass (described in Section 3.1.3.2). In the future, an alternative solution may be to allow inter-regional trade in FodderGrass products.

4.1.6 Unmanaged Forest, Unmanaged Pasture, Grassland, Shrubland

All four of these land types were compiled from the HYDE data, with the unmanaged forest and pasture calculated as total forest and pasture minus the managed forms of each of these lands, calculated above. All four of these land types are adjusted to accommodate any ―extra" cropland in regions where the unadjusted harvested:cropped ratio exceeded 2.5.

4.2 Carbon Contents

GCAM separates carbon pools into two categories: (1) vegetation, and (2) soil carbon. The vegetation component includes all carbon in live vegetation. Short-lived pools (litter, dead vegetation) are not considered.

4.2.1 Vegetation carbon contents

Vegetation carbon contents are derived for any sub-regional AEZ based on the specific land types from the SAGE (Ramankutty and Foley 1999) database, along with assumptions about the carbon contents of those specific land types. Specifically, the method is as follows. First, the composition of SAGE's 14 natural vegetation classifications is calculated in each region and AEZ for each of the five GCAM natural vegetation categories. Next, carbon contents are assigned to each of the SAGE 14 natural vegetation types, based on literature estimates, shown in Table 4.4. The carbon density of each region/AEZ/GCAM land type is then calculated as the weighted average of the carbon contents of the SAGE natural vegetation types within the GCAM natural vegetation types, for each region and AEZ. For instance, GCAM forest in USA AEZ 9 is 53% temperate needleleaf evergreen forest, 12% temperate deciduous forest, 1% boreal evergreen forest, and 34% mixed evergreen/deciduous forest. Therefore the average carbon content of USA AEZ 9 forest is (160)(0.53) + (135)(0.12) + (90)(0.01) + (103)(0.34) = 137 MgC/ha, or 13.7 kgC/m2. Similar calculations are used for vegetation carbon contents for forest, grassland, shrubland, tundra, and rock/ice/desert.

Unmanaged pasture vegetation carbon contents are set equal to the region/AEZ's corresponding SAGE grassland carbon contents. Managed pasture carbon contents are set equal to one half of unmanaged pasture carbon contents. Managed forest vegetation carbon contents are set equal to one half of the unmanaged forest carbon contents. These values reflect several aspects of the managed systems. First, there will be less vegetation in grazed and logged ecosystems over the long term, on average, because vegetation recovery does not happen immediately following disturbance. Second, the peak biomass of these systems will often be lower than corresponding ungrazed or unlogged systems. We note that the specific multipliers calculating the average carbond density of managed forests and pastures from their corresponding unmanaged values may be a topic worth further investigation in the future.

Cropland vegetation carbon contents are calculated based on yields, crop moisture contents, and harvest indices. Cropland vegetation biomass is calculated by the following equation:

$$C = \frac{Yield}{HarvestIndex} \times CarbonContent \times (1 - WaterContent) \times (1 + RoottoShoot) \times 0.5 \ ,$$

where yield is in kg crop per m^2 of cropland, and all other parameters are unitless. HarvestIndex is the ratio of the harvested portion of the crop to the total aboveground crop biomass; CarbonContent is the portion of the dry biomass that is carbon, assumed to be 0.45; WaterContent is the portion of the mass of the crop that is water at the time of harvest; and RoottoShoot is the root mass of the plant divided by the above-ground mass at harvest. The total vegetation carbon at harvest is multiplied by 0.5 in order to approximate the average carbon content over the course of the entire calendar year. Note that for perennial bioenergy crops, the root portion of the plant is assumed to be long-lived, and as such is not multiplied by 0.5.

Parameter values for most crops come from the residue biomass calculations (see Tables A5 and A6); exceptions include forage crops and bioenergy crops, as they are not considered eligible for production of residue bioenergy. Forage crops are considered to have a water content of 74%, harvest index of 1, and root:shoot ratio of 0.18 (West 2011). Hay (―FodderGrass”) is assigned a water content of 15%, harvest index of 1, and root:shoot ratio of 0.87 (West 2011). Switchgrass is also assigned a water content of 15% and a harvest index of 1. The root:shoot ratios in the literature span a wide range; four studies surveyed present estimates of 0.56 (Zan et al. 2001), 0.77 (Garten et al. 2011), 2.72 (Ma et al. 2001), and 2.97 (Frank et al. 2005). At present, we are assuming 0.77; this value is also used by the EPIC model.

Table 4.4: Average vegetation carbon density by SAGE biome type, and specific data source.

GCAM category	**SAGE category**	**C density (MgC/ha)**	**Source**
AllForestLand	Tropical Evergreen Forest/Woodland	200	Houghton 1999, Table 1, tropical equatorial forest
AllForestLand	Tropical Deciduous Forest/Woodland	140	Houghton 1999, Table 1, tropical seasonal forest
AllForestLand	Temperate Broadleaf Evergreen Forest/Woodland	154	King et al 1997, Table III, Temperate evergreen seasonal broadleaved forest
AllForestLand	Temperate Needleleaf Evergreen Forest/Woodland	160	Houghton 1999, Table 1, temperate evergreen forest
AllForestLand	Temperate Deciduous Forest/Woodland	135	Houghton 1999, Table 1, temperate deciduous forest
AllForestLand	Boreal Evergreen Forest/Woodland	90	Houghton 1999, Table 1, boreal forest
AllForestLand	Boreal Deciduous Forest/Woodland	90	Houghton 1999, Table 1, boreal forest
AllForestLand	Evergreen/Deciduous Mixed Forest/Woodland	103 (AEZs 1-12)	King et al 1997, Table III, Cold deciduous forest with evergreens
AllForestLand	Evergreen/Deciduous Mixed Forest/Woodland	50 (AEZs 13-18)	Olson et al 1982, Table 2, Northern or Maritime Taiga
GrassLand	Savanna	25	King et al 1997, Table III, tall/med/shrt grassland w/ 10-40% woody cover
GrassLand	Grassland/Steppe	4 – 10*[4]	Houghton 1999, Table 1, grassland
ShrubLand	Dense Shrubland	55	Houghton 1999, Table 1, tropical woodland
ShrubLand	Open Shrubland	27	Houghton 1999, Table 1, woodland
Tundra	Tundra	9	King et al 1997, Table III, Arctic/alpine tundra, mossy bog
RockIceDesert	Desert	1	King et al 1997, Table III, Desert
RockIceDesert	Polar Desert/Rock/Ice	0	

4.2.2 Soil carbon contents

Soil carbon contents for all unmanaged biomes are calculated in similar fashion as vegetation carbon contents; values assumed are shown in Table 4.5.

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[4] Grassland carbon contents are assumed to increase with moisture, such that AEZs 1,7, and 13 have 4 MgC/ha, and AEZs 6, 12, and 18 have 10 MgC/ha (values based on Gibbs et al., 2008).

Table 4.5: Average soil carbon density by SAGE biome type, and specific data source.

GCAM category	**SAGE category**	**C density (MgC/ha)**	**Source**
AllForestLand	Tropical Evergreen Forest/Woodland	98	Houghton 1999, tropical equatorial forest
AllForestLand	Tropical Deciduous Forest/Woodland	98	Houghton 1999, tropical seasonal forest
AllForestLand	Temperate Broadleaf Evergreen Forest/Woodland	71	King et al. 1997, Table III, Temperate evergreen seasonal broadleaved forest
AllForestLand	Temperate Needleleaf Evergreen Forest/Woodland	134	Houghton 1999, Table 1, temperate evergreen forest
AllForestLand	Temperate Deciduous Forest/Woodland	134	Houghton 1999, Table 1, temperate deciduous forest
AllForestLand	Boreal Evergreen Forest/Woodland	206	Houghton 1999, Table 1, boreal forest
AllForestLand	Boreal Deciduous Forest/Woodland	206	Houghton 1999, Table 1, boreal forest
AllForestLand	Evergreen/Deciduous Mixed Forest/Woodland	111 (AEZs 1-12)	King et al 1997, Table III, Cold deciduous forest with evergreens
AllForestLand	Evergreen/Deciduous Mixed Forest/Woodland	206 (AEZs 13-18)	Houghton 1999, Table 1, boreal forest
GrassLand	Savanna	95	King et al 1997, Table III, tall/med/shrt grassland w/ 10-40% woody cover
GrassLand	Grassland/Steppe	60 - 185*	IGBP; checked with many sources
ShrubLand	Dense Shrubland	69	Houghton 1999, Table 1, tropical woodland
ShrubLand	Open Shrubland	69	Houghton 1999, Table 1, woodland
Tundra	Tundra	100 – 300*	Zinke et al, Table 4.1, checked with IGBP soils map
RockIceDesert	Desert	38	King et al 1997, Table III, Desert
RockIceDesert	Polar Desert/Rock/Ice	85	No source available; value set for consistency with IGBP soils map

For some ecosystems, several studies were considered in deriving the soil carbon density estimate used in GCAM. For example, the Evergreen/Deciduous Mixed Forest/Woodland category includes Olsen's (1983) ―Northern or Maritime Taiga" as well as temperate mixed forests, which differ in both vegetation and soil carbon contents. The Northern or Maritime Taiga (AEZs 13-18) soil carbon contents are quite high, similar to other boreal forests, whereas the temperate forests of this SAGE category are more consistent with the values presented by King et al. (1997) for cold deciduous forests with evergreens. In addition, the soil carbon density estimate of grassland/steppe varies significantly across studies (see Table 4.6).

Table 4.6: Literature estimates of average grassland soil carbon density.

Study	Ecosystem Type	C density (MgC/ha)
Gibbs et al. (2008)	Tropical Grassland (Africa)	41
Houghton (1999)	Grassland (Latin America)	42
Jain and Yang (2005)	Grassland	47
Houghton (1999)	Grassland (Tropical Asia)	50
Gibbs et al. (2008)	Tropical Grassland (LAM, AUS)	60
Adams (ORNL; unpubl)	Dry Steppe	76
Gibbs et al. (2008)	Tropical Grassland (Asia)	80
Zinke et al. (1984)	Misc grassland	87
King et al. (1997)	Various grasslands (min value)	88
Zinke et al. (1984)	Cool grassland	123
King et al. (1997)	Various grasslands (max value)	128
Houghton (1999)	Grassland (all but LAM and SEA)	189
Schlesinger (1977)	Temperate grassland	192
Zinke et al. (1984)	Cold rangeland	247
Adams (ORNL; unpubl)	Moist Steppe	260

Note that of the studies shown above, only Zinke et al. (1984) is a primary study on this topic, and only Schlesinger (1977) cites the primary sources used in deriving the values shown. None of the other studies cite their sources, but all of these values represent averages of grassland carbon contents over large geographic areas. Nevertheless, the variation spans the range of all other ecosystem types considered (deserts on the lower end, boreal forests on the upper end), and even within a subset of grassland types (e.g. temperate grasslands) there is a wide range. This variation within a given ecosystem type may be due to precipitation, but the only study to present different values for dry as opposed to moist grasslands (Adams) is a website with no supporting publication.

We therefore use the IGBP-based estimates (Global Soil Data Task Group 2000) of soil carbon density to inform our assumed carbon densities. Specifically, our values adhere to the following: (1) Lower temperature grasslands have higher soil carbon contents, with each AEZ temperature step (e.g. 1 to 7 to 13) increasing by 25 MgC/ha; and (2) More moist grasslands have higher carbon contents, with each AEZ precipitation step (e.g. 1 to 2 to 3) increasing by 15 MgC/ha. The comparison between this method and the IGBP-based total carbon stocks by AEZ for SAGE's ―Grassland/Steppe" natural vegetation type is shown below; note that values shown do not consider deductions for cropland or pasture, nor do they include savanna. As such these values are different from GCAM's ―Grassland" soil carbon stocks, shown in Table 4.7.

Table 4.7: GCAM grassland soil carbon density assumptions by AEZ, applied to all regions. Also shown are the consequent soil carbon pools by each AEZ, compared with IGBP (Global Soil Data Task Group 2000) aggregation of grassland soil carbon by AEZ.

AEZ	Avg C density	Total	IGBP Total
	MgC/ha	PgC	PgC

AEZ1	60	4.28	4.16
AEZ2	75	3.64	3.30
AEZ3	90	0.59	0.70
AEZ4	105	0.93	0.98
AEZ5	120	1.77	1.80
AEZ6	135	2.91	3.62
AEZ7	85	33.55	35.48
AEZ8	100	29.21	30.63
AEZ9	115	9.16	8.93
AEZ10	130	5.98	6.04
AEZ11	145	3.86	3.36
AEZ12	160	12.84	10.73
AEZ13	110	17.80	17.76
AEZ14	125	12.15	13.03
AEZ15	140	6.63	8.45
AEZ16	155	3.57	3.10
AEZ17	170	0.23	0.19
AEZ18	185	0.00	0.00
Total		149.11	152.26

The soil carbon content of tundra also varies significantly due to moisture; Zinke et al. (1984) reports that dry tundra is as low as 31 MgC/ha, and rain tundra is as high as 366 MgC/ha. Because the IGBP map suggests a narrower range, we assume that tundra carbon contents increase from 100 MgC/ha in dry AEZs (1, 7, 13) to 300 MgC/ha in moist AEZs (6, 12, 18). This results in 111 PgC of soil carbon globally in tundra, close to the IGBP-based estimate of 108. Note that because tundra is not involved in any economic land allocation, these assumed values do not affect the model output, but may nevertheless be useful for researching wishing to report total soil carbon pools in GCAM.

Soil carbon in pasture is set equal to the values in the GCAM grassland for each region and AEZ; managed pasture is equal to unmanaged pasture. The literature on the effects of grazing on soil carbon indicates that conversion of native land to pasture may increase or decrease soil carbon, but the effect tends to be quite small (<10%; Guo and Gifford 2002; Murty et al. 2002).

The literature on soil carbon in croplands indicates that tillage generally decreases soil carbon by about 30% from the reference system, in the soil depths that are typically affected by tillage (Houghton 1999; Murty et al. 2002; Davidson and Ackerman 1993). Only the top 30 cm are affected by tillage (T. West, pers. comm.), and the vast majority of studies only assay the top 30cm, due in part to the difficulty of deeper sampling and the lack of any tillage effect below this depth. However, our model input values are based on soil carbon to 100cm depth. The top 30cm of the soil profile contains about 63% of the soil carbon in forest, 56% in grassland, and 47% in shrubland (Tobbagy and Jackson 2000), with the remainder unaffected by tillage. In other words, the effect of cultivation on soil carbon assumed by Houghton (1999) may be an over-estimate, if the effect of tillage is applied to the entire top meter of soil (West et al. 2004). In any case, the values that we are currently using are from Houghton (1999), and are generally about 30% less than unmanaged lands in the same AEZ.

Finally, the soil carbon values assumed for bioenergy crops are equal to the corresponding values for pastures and grasslands of the region and AEZ. This is because the bioenergy crop is assumed to have the characteristics of switchgrass, a perennial grass that is grown without annual tillage.

4.2.3 Physical and Economic Accounting for the Carbon Content in Biomass Energy

In accounting for the carbon implications of biomass energy, it is critical to distinguish two stores of carbon. The first store is the carbon that is maintained in the terrestrial system as a consequence of dedicating land to biomass, which is distinct from the second store – the carbon that is included in the harvested biomass plant. Regardless of the type of biomass, terrestrial carbon includes soil carbon and any root or crown carbon that may persist for perennial biomass crops such as switchgrass. This terrestrial carbon is the key driver for any emissions of CO_2 from land-use change. For example, when land is converted from a use, such as forests, with higher terrestrial carbon, to biomass energy crops, there is an emission of CO_2 resulting from the decrease in terrestrial carbon. Conversely, there is a net uptake of CO_2 when land is converted from a use with lower terrestrial carbon to a use with a higher value. When we model policies in GCAM that value the carbon in land or penalize land use emissions, it is the terrestrial carbon that is relevant, not the amount of carbon in the harvested biomass energy plant.

The second store of carbon, the carbon in the harvested plant, is the relevant quantity for carbon emissions policy in the energy system. One possible strategy for accounting for this carbon is to assume it is net zero on a life cycle basis since any CO_2 emitted from burning or using the biomass for energy was taken out of the atmosphere as the plant grew. This simple strategy works well until CO_2 capture and storage (CCS) technologies are considered. Even if biomass can be considered as having net zero carbon on a life-cycle basis, there is still carbon in the biomass plant. If CCS technologies are available, there is a way to use that biomass while avoiding CO_2 emissions, in effect resulting in net negative life cycle emissions. However, the accounting of the carbon in biomass energy has to provide the correct signal to use CCS in terms of economics and physical measurement of emissions, and a carbon content of zero by itself is not adequate.

There are multiple strategies for accounting for the carbon in biomass, which, fortunately, are equivalent in terms of the net accounting and economic incentives. For GCAM, our current strategy involves two parts, and we will call it the –upstream/downstream” strategy here. The first is the upstream part where we account for the carbon uptake in growing the biomass and also subsidize the biomass for that carbon if there is a carbon tax or price in place during that period. In the second step, which is the downstream step, biomass is treated like a carbonaceous fuel with its carbon content accounted for like the fossil fuels, and it is taxed or penalized for carbon emissions if there is a carbon policy.

If there is no CCS available, then both the physical and the economic accounting of the carbon in biomass nets to zero. That is, the carbon uptake in growing the biomass is exactly offset by the carbon emissions in using the biomass for energy, and any carbon subsidy received upstream is exactly counteracted by the carbon tax or penalty paid downstream. So the net effect is the same as if biomass were assumed to have zero carbon content. But biomass will still be affected by the climate policy as the fossil fuels with which it competes become more costly due to their carbon emissions penalties.

The main advantage of this upstream/downstream accounting strategy is that, in addition to being equivalent to assuming a zero carbon content when appropriate, it also provides the economic incentive to avoid carbon emissions from biomass when CCS technologies are available. At the point at which the biomass reaches the energy system, it is considered a carbonaceous fuel and would be penalized under an emissions policy. If this cost penalty is sufficiently high, it will provide the incentive to use CCS to avoid the emissions penalty. And with CCS, the accounting for the uptake of emissions upstream combined with the zero or near zero emissions for the CCS technology downstream results in net negative emissions.

This upstream/downstream accounting strategy is economically equivalent to an alternative strategy where biomass is treated as having zero carbon content everywhere but CCS technologies are paid a credit for capturing CO_2 (rather than avoiding paying an emissions penalty like they would with fossil fuels). Sometimes we explain the results in this manner for convenience, and it is implied when we show negative emissions assigned to the electric power sector in our results. Fortunately, this strategy is equivalent and would provide the same economic incentives throughout the chain from biomass farmers to users in the energy system. For example, although the upstream price would not be subsidized for carbon, the equilibrium upstream price would still reflect that same carbon value as the CCS credit paid in the energy system would increase the demand for biomass to the same value as if there had been a subsidy. Although this strategy is equivalent, it is not used internally to GCAM as it less convenient to implement and involves more special cases. The upstream/downstream strategy can be applied more generically with the way we account for fossil fuel carbon.

4.2.4 Land Values and Land Sharing Logit Exponents

Ultimately, changes in future land shares in GCAM are determined by the relative profit rates of the different uses, and the logit exponents assumed on switching between the different land types. For lands involved in economic production (cropland, managed pasture, and managed forest), the profit rates are endogenous, computed as the profit from primary commodities produced on land, in addition to the value of the carbon in the land (if carbon in land is priced). For unmanaged lands, there is no revenue stream from primary commodity production, so this portion of the profit rates is exogenous. In the current data set, the unmanaged land value is derived as the average revenue generated on all land that is involved in economic production in the given sub-regional AEZ, according to the GTAP (2009) Land Use Database.

The calculation of the economic value of unmanaged land is as follows. The GTAP (2009) estimates of the value from thirteen commodity classes by 87 countries and 18 AEZs are aggregated by region and AEZ. Animal production is omitted from this calculation, as the production of secondary goods is not directly associated with land in GCAM. Next, the total land cover attributed to the managed uses is aggregated by region and AEZ. This calculation excludes pasture and ―other arable land,” but includes the production of fodder crops. Then, the total land value is divided by the quantity of land in economic production in each sub-regional AEZ, yielding an estimate of the land value per unit of land area. This is the value assumed of any unmanaged lands in any nest for the given sub-regional AEZ.

The land sharing logit exponents in GCAM 3.0 would ideally reflect literature estimates of the own-price elasticity of different land use types. Note that the derivation of a logit exponent from an elasticity is not entirely straightforward, and is documented in detail in Wise and Calvin (2011). However, for most of the land nests in GCAM 3.0 there is no such literature; as such, only the cropland logit exponents reflect literature estimates of the historical own-price elasticity of crop production (detailed in Wise and Calvin 2011). For all remaining land uses, the assumed logit exponents in the current data set were largely derived through analysis of model output, and are a good candidate for sensitivity analyses (see Table 4.8 for assumptions). In general, the exponents are set such land switches more easily (higher logit exponent = more price-induced shifting) between land use types that are mostly similar. For instance, forest land can easily switch between managed and unmanaged forest, but would be less likely to switch towards or away from pasture land. Logit exponents assumed for arid AEZs are generally low; this is designed to avoid results that are ecologically infeasible, such as expansions of forests in arid lands due to land use policies that incentivize land-use types with high carbon densities. This is also the reason for the very low value assumed regulating the switching between grassland and shrubland.

Table 4.8. Assumed logit exponents of GCAM land nodes. Values apply to the land uses underneath the specified land node in Figure 1.2.

LandNode	Non-arid AEZs	Arid AEZs
AgroForestLand	1	0.5
AllPastureLand	3	1.5
AgroForest_NonPasture	1.25	0.625
AllForestLand	1.75	0.875
GrassShrubLand	0.05	0.05
CropLand	1.75	0.875

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6 Appendix A: Mapping lists

GCAM currently divides the world into 14 geopolitical regions. Some of these regions (e.g., the United States, Canada, Japan) are individual countries, while other regions (e.g., Africa, Latin America) are aggregates of numerous countries. Table A.1 provides a country-to-region mapping for GCAM.

Table A.1: Country to region list

Countries	**GCAM Region**
Afghanistan	Southeast Asia
Albania	Eastern Europe
Algeria	Africa
American Samoa	Southeast Asia
Andorra	Western Europe
Angola	Africa
Anguilla	Latin America
Antigua and Barbuda	Latin America
Argentina	Latin America
Armenia	Former Soviet Union
Aruba	Latin America
Australia	Australia_NZ
Austria	Western Europe
Azerbaijan	Former Soviet Union
Azerbaijan, Republic of	Former Soviet Union
Bahamas	Latin America
Bahrain	Middle East
Bangladesh	Southeast Asia
Barbados	Latin America
Belarus	Former Soviet Union
Belgium	Western Europe
Belgium-Luxembourg	Western Europe
Belize	Latin America
Benin	Africa
Bermuda	Western Europe
Bhutan	Southeast Asia
Bolivia (Plurinational State of)	Latin America
Bosnia and Herzegovina	Eastern Europe
Botswana	Africa
Brazil	Latin America

British Virgin Islands	Latin America
Brunei Darussalam	Southeast Asia
Bulgaria	Eastern Europe
Burkina Faso	Africa
Burundi	Africa
Cambodia	China
Cameroon	Africa
Canada	Canada
Cape Verde	Africa
Cayman Islands	Latin America
Central African Republic	Africa
Chad	Africa
Chile	Latin America
China	China
China, Hong Kong SAR	China
China, Macao SAR	China
Christmas Island	Australia_NZ
Cocos (Keeling) Islands	Australia_NZ
Colombia	Latin America
Comoros	Africa
Congo	Africa
Congo, Dem Republic of	Africa
Congo, Democratic Republic of	Africa
Congo, Republic of	Africa
Cook Islands	Australia_NZ
Costa Rica	Latin America
Cote dIvoire	Africa
Croatia	Eastern Europe
Cuba	Latin America
Cyprus	Western Europe
Czech Republic	Eastern Europe
Czechoslovakia	Eastern Europe
Democratic Peoples Republic of Korea	China
Denmark	Western Europe
Djibouti	Africa
Dominica	Latin America
Dominican Republic	Latin America
Ecuador	Latin America
Egypt	Africa
El Salvador	Latin America
Equatorial Guinea	Africa

Eritrea	Africa
Estonia	Former Soviet Union
Ethiopia	Africa
Ethiopia PDR	Africa
Falkland Islands	Latin America
Faroe Islands	Western Europe
Fiji	Southeast Asia
Fiji Islands	Southeast Asia
Finland	Western Europe
France	Western Europe
French Guiana	Latin America
French Polynesia	Southeast Asia
Gabon	Africa
Gambia	Africa
Georgia	Former Soviet Union
Germany	Western Europe
Ghana	Africa
Gibraltar	Western Europe
Greece	Western Europe
Greenland	Western Europe
Grenada	Latin America
Guadeloupe	Latin America
Guam	Southeast Asia
Guatemala	Latin America
Guinea	Africa
Guinea-Bissau	Africa
Guyana	Latin America
Haiti	Latin America
Honduras	Latin America
Hungary	Eastern Europe
Iceland	Western Europe
India	India
Indonesia	Southeast Asia
Iran (Islamic Republic of)	Middle East
Iraq	Middle East
Ireland	Western Europe
Israel	Middle East
Italy	Western Europe
Jamaica	Latin America
Japan	Japan
Jordan	Middle East

Kazakhstan	Former Soviet Union
Kenya	Africa
Kiribati	Southeast Asia
Kuwait	Middle East
Kyrgyzstan	Former Soviet Union
Lao Peoples Democratic Republic	Southeast Asia
Laos	Southeast Asia
Latvia	Former Soviet Union
Lebanon	Middle East
Lesotho	Africa
Liberia	Africa
Libyan Arab Jamahiriya	Africa
Liechtenstein	Western Europe
Lithuania	Former Soviet Union
Luxembourg	Western Europe
Macedonia,The Fmr Yug Rp	Eastern Europe
Madagascar	Africa
Malawi	Africa
Malaysia	Southeast Asia
Maldives	Southeast Asia
Mali	Africa
Malta	Western Europe
Marshall Islands	Southeast Asia
Martinique	Western Europe
Mauritania	Africa
Mauritius	Africa
Mexico	Latin America
Micronesia,Fed States of	Southeast Asia
Micronesia, Federated States of	Southeast Asia
Moldova	Former Soviet Union
Moldova, Republic of	Former Soviet Union
Mongolia	China
Montenegro	Eastern Europe
Montserrat	Latin America
Morocco	Africa
Mozambique	Africa
Myanmar	Southeast Asia
Namibia	Africa
Nauru	Southeast Asia
Nepal	Southeast Asia
Netherlands	Western Europe

Netherlands Antilles	Latin America
New Caledonia	Southeast Asia
New Zealand	Australia_NZ
Nicaragua	Latin America
Niger	Africa
Nigeria	Africa
Niue	Australia_NZ
Norfolk Island	Southeast Asia
Norway	Western Europe
Occupied Palestinian Territory	Middle East
Oman	Middle East
Pacific Is	Southeast Asia
Pacific Islands Trust Tr	Southeast Asia
Pakistan	Southeast Asia
Palau	Southeast Asia
Palestine, Occupied Tr.	Middle East
Panama	Latin America
Papua New Guinea	Southeast Asia
Paraguay	Latin America
Peru	Latin America
Philippines	Southeast Asia
Poland	Eastern Europe
Portugal	Western Europe
Puerto Rico	USA
Qatar	Middle East
Republic of Korea	Korea
Réunion	Africa
Romania	Eastern Europe
Russian Federation	Former Soviet Union
Rwanda	Africa
Saint Helena	Africa
Saint Kitts and Nevis	Latin America
Saint Lucia	Latin America
Saint Pierre and Miquelon	Canada
Saint Vincent and the Grenadines	Latin America
Samoa	Southeast Asia
Sao Tome and Principe	Africa
Saudi Arabia	Middle East
Senegal	Africa
Serbia	Eastern Europe
Seychelles	Africa

Sierra Leone	Africa
Singapore	Southeast Asia
Slovakia	Eastern Europe
Slovenia	Eastern Europe
Solomon Islands	Southeast Asia
Somalia	Africa
South Africa	Africa
Spain	Western Europe
Sri Lanka	Southeast Asia
Sudan	Africa
Suriname	Latin America
Swaziland	Africa
Sweden	Western Europe
Switzerland	Western Europe
Syrian Arab Republic	Middle East
Tajikistan	Former Soviet Union
Thailand	Southeast Asia
The former Yugoslav Republic of Macedonia	Eastern Europe
Timor-Leste	Southeast Asia
Togo	Africa
Tokelau	Australia_NZ
Tonga	Southeast Asia
Trinidad and Tobago	Latin America
Tunisia	Africa
Turkey	Western Europe
Turkmenistan	Former Soviet Union
Turks and Caicos Islands	Latin America
Tuvalu	Southeast Asia
Uganda	Africa
Ukraine	Former Soviet Union
United Arab Emirates	Middle East
United Kingdom	Western Europe
United Republic of Tanzania	Africa
United States of America	USA
Uruguay	Latin America
US Virgin Islands	Latin America
USSR	Former Soviet Union
Uzbekistan	Former Soviet Union
Vanuatu	Southeast Asia
Venezuela (Bolivarian Republic of)	Latin America
Viet Nam	China

Wallis and Futuna Is	Australia_NZ
Wallis and Futuna Islands	Australia_NZ
Yemen	Middle East
Yugoslav SFR	Eastern Europe
Yugoslavia SFR	Eastern Europe
Zambia	Africa
Zimbabwe	Africa

Table A.2: FAO PRODSTAT to GCAM commodity list

Item	GCAM Commodity
Agave Fibres Nes	FiberCrop
Alfalfa for forage and silage	FodderHerb
Almonds, with shell	MiscCrop
Anise, badian, fennel, corian.	MiscCrop
Apples	MiscCrop
Apricots	MiscCrop
Arecanuts	MiscCrop
Artichokes	MiscCrop
Asparagus	MiscCrop
Avocados	MiscCrop
Bambara beans	MiscCrop
Bananas	MiscCrop
Barley	OtherGrain
Beans, green	MiscCrop
Beans, dry	MiscCrop
Beets for Fodder	FodderHerb
Berries Nes	MiscCrop
Blueberries	MiscCrop
Brazil nuts, with shell	MiscCrop
Broad beans, horse beans, dry	MiscCrop
Buckwheat	OtherGrain
Cabbage for Fodder	FodderHerb
Cabbages and other brassicas	MiscCrop
Canary seed	OtherGrain
Carobs	MiscCrop
Carrots and turnips	MiscCrop
Carrots for Fodder	FodderHerb
Cashew nuts, with shell	MiscCrop
Cashewapple	MiscCrop
Cassava	Root_Tuber
Castor oil seed	OilCrop
Cauliflowers and broccoli	MiscCrop

Cereals, nes	OtherGrain
Cherries	MiscCrop
Chestnuts	MiscCrop
Chick peas	MiscCrop
Chicory roots	MiscCrop
Chillies and peppers, dry	MiscCrop
Chillies and peppers, green	MiscCrop
Cinnamon (canella)	MiscCrop
Citrus fruit, nes	MiscCrop
Clover for forage and silage	FodderHerb
Cloves	MiscCrop
Cocoa beans	MiscCrop
Coconuts	PalmFruit
Coffee, green	MiscCrop
Cotton lint	Cotton_Fiber
Cow peas, dry	MiscCrop
Cranberries	MiscCrop
Cucumbers and gherkins	MiscCrop
Currants	MiscCrop
Dates	MiscCrop
Eggplants (aubergines)	MiscCrop
Fibre Crops Nes	FiberCrop
Figs	MiscCrop
Flax fibre and tow	FiberCrop
Fonio	OtherGrain
forage Products	FodderGrass
Fruit Fresh Nes	MiscCrop
Fruit, tropical fresh nes	MiscCrop
Garlic	MiscCrop
Ginger	MiscCrop
Gooseberries	MiscCrop
Grapefruit (inc. pomelos)	MiscCrop
Grapes	MiscCrop
Grasses Nes for forage;Sil	FodderGrass
Green Oilseeds for Silage	FodderHerb
Groundnuts, with shell	OilCrop
Gums Natural	na
Hazelnuts, with shell	MiscCrop
Hemp Tow Waste	FiberCrop
Hempseed	OilCrop
Hops	MiscCrop

Jojoba Seeds	OilCrop
Jute	FiberCrop
Karite Nuts (Sheanuts)	OilCrop
Kiwi fruit	MiscCrop
Kolanuts	MiscCrop
Leeks, other alliaceous veg	MiscCrop
Leguminous for Silage	FodderHerb
Leguminous vegetables, nes	MiscCrop
Lemons and limes	MiscCrop
Lentils	MiscCrop
Lettuce and chicory	MiscCrop
Linseed	OilCrop
Lupins	MiscCrop
Maize	Corn
Maize for forage and silage	FodderHerb
Maize, green	Corn
Mangoes, mangosteens, guavas	MiscCrop
Manila Fibre (Abaca)	FiberCrop
Mate	MiscCrop
Melonseed	OilCrop
Millet	OtherGrain
Mixed grain	OtherGrain
Mushrooms and truffles	MiscCrop
Mustard seed	OilCrop
Natural rubber	na
Nutmeg, mace and cardamoms	MiscCrop
Nuts, nes	MiscCrop
Oats	OtherGrain
Oil palm fruit	PalmFruit
Oilseeds, Nes	OilCrop
Okra	MiscCrop
Olives	OilCrop
Onions (inc. shallots), green	MiscCrop
Onions, dry	MiscCrop
Oranges	MiscCrop
Other Bastfibres	FiberCrop
Other melons (inc.cantaloupes)	MiscCrop
Papayas	MiscCrop
Peaches and nectarines	MiscCrop
Pears	MiscCrop
Peas, dry	MiscCrop

Peas, green	MiscCrop
Pepper (Piper spp.)	MiscCrop
Peppermint	MiscCrop
Persimmons	MiscCrop
Pigeon peas	MiscCrop
Pineapples	MiscCrop
Pistachios	MiscCrop
Plantains	MiscCrop
Plums and sloes	MiscCrop
Popcorn	Corn
Poppy seed	OilCrop
Potatoes	Root_Tuber
Pulses, nes	MiscCrop
Pumpkins for Fodder	na
Pumpkins, squash and gourds	MiscCrop
Pyrethrum,Dried	MiscCrop
Quinces	MiscCrop
Quinoa	OtherGrain
Ramie	FiberCrop
Rapeseed	OilCrop
Raspberries	MiscCrop
Rice, paddy	Rice
Roots and Tubers, nes	Root_Tuber
Rye	OtherGrain
Rye grass for forage and silage	FodderGrass
Safflower seed	OilCrop
Seed cotton	Cotton_Total
Sesame seed	OilCrop
Sisal	FiberCrop
Sorghum	OtherGrain
Sorghum for forage and silage	FodderGrass
Sour cherries	MiscCrop
Soybeans	OilCrop
Spices, nes	MiscCrop
Spinach	MiscCrop
Stone fruit, nes	MiscCrop
Strawberries	MiscCrop
String beans	MiscCrop
Sugar beet	SugarCrop
Sugar cane	SugarCrop
Sugar crops, nes	SugarCrop

Sunflower seed	OilCrop
Swedes for Fodder	FodderHerb
Sweet potatoes	Root_Tuber
Tangerines, mandarins, clem.	MiscCrop
Taro (cocoyam)	Root_Tuber
Tea	MiscCrop
Tea Nes	MiscCrop
Tobacco, unmanufactured	MiscCrop
Tomatoes	MiscCrop
Triticale	OtherGrain
Tung Nuts	OilCrop
Turnips for Fodder	FodderHerb
Vanilla	MiscCrop
Vegetables fresh nes	MiscCrop
Vegetables Roots Fodder	FodderHerb
Vetches	FodderHerb
Walnuts, with shell	MiscCrop
Watermelons	MiscCrop
Wheat	Wheat
Yams	Root_Tuber
Yautia (cocoyam)	Root_Tuber

Table A.3: Mapping and calorie conversions for FAO Commodity Balances crops

Item	GCAM Commodity	MCal per tonne
Abaca	FiberCrop	0
Alcohol, Non-Food	na	0
Apples	MiscCrop	480
Bananas	MiscCrop	600
Barley	OtherGrain	3320
Beans	MiscCrop	3410
Beer	na	0
Beverages, Alcoholic	na	0
Beverages, Fermented	na	0
Brans	na	0
Cassava	Root_Tuber	1090
Cereals, Other	OtherGrain	3400
Citrus, Other	MiscCrop	260
Cloves	MiscCrop	3230
Cocoa Beans	MiscCrop	4140
Coconut Oil	PalmFruit	8840
Coconuts - Incl Copra	PalmFruit	1840
Coffee	MiscCrop	470

Copra Cake	PalmFruit	6360
Cotton Lint	FiberCrop	0
Cottonseed	OilCrop	2530
Cottonseed Cake	OilCrop	2530
Cottonseed Oil	OilCrop	8840
Dates	MiscCrop	1560
Fruits, Other	MiscCrop	450
Grapefruit	MiscCrop	160
Grapes	MiscCrop	530
Groundnut Cake	OilCrop	3630
Groundnut Oil	OilCrop	8840
Groundnuts (in Shell Eq)	OilCrop	4140
Groundnuts (Shelled Eq)	na	0
Hard Fibres, Other	FiberCrop	0
Jute	FiberCrop	0
Jute-Like Fibres	FiberCrop	0
Lemons, Limes	MiscCrop	150
Maize	Corn	3560
Maize Germ Oil	Corn	8840
Millet	OtherGrain	3400
Molasses	SugarCrop	2320
Nuts	MiscCrop	2620
Oats	OtherGrain	3850
Oilcrops Oil, Other	OilCrop	8840
Oilcrops, Other	OilCrop	3870
Oilseed Cakes, Other	OilCrop	2610
Olive Oil	OilCrop	8840
Olives	OilCrop	1750
Onions	MiscCrop	240
Oranges, Mandarines	MiscCrop	340
Other Bastfibres	FiberCrop	0
Other melons (inc.cantaloupes)	MiscCrop	170
Palm Oil	PalmFruit	8840
Palmkernel Cake	PalmFruit	5140
Palmkernel Oil	PalmFruit	8840
Palmkernels	PalmFruit	5140
Peas	MiscCrop	3460
Pepper	MiscCrop	2760
Pimento	MiscCrop	3180
Pineapples	MiscCrop	260
Plantains	MiscCrop	750

Potatoes	Root_Tuber	670
Pulses, Other	MiscCrop	3400
Rape and Mustard Cake	OilCrop	4940
Rape and Mustard Oil	OilCrop	8840
Rape and Mustardseed	OilCrop	4940
Rice (Milled Equivalent)	na	0
Rice (Paddy Equivalent)	Rice	2800
Ricebran Oil	Rice	8840
Roots and Tuber Dry Equiv	na	0
Roots, Other	Root_Tuber	910
Rubber	na	0
Rye	OtherGrain	3190
Sesameseed	OilCrop	5730
Sesameseed Cake	OilCrop	3760
Sesameseed Oil	OilCrop	8840
Sisal	FiberCrop	0
Soft-Fibres, Other	FiberCrop	0
Sorghum	OtherGrain	3430
Soyabean Cake	OilCrop	2610
Soyabean Oil	OilCrop	8840
Soyabeans	OilCrop	3350
Spices, Other	MiscCrop	3370
Spinach	MiscCrop	160
Stone fruit, nes	MiscCrop	520
Strawberries	MiscCrop	280
String beans	MiscCrop	270
Sugar (Raw Equivalent)	SugarCrop	3730
Sugar Beet	SugarCrop	700
Sugar Cane	SugarCrop	300
Sugar, Non-Centrifugal	na	0
Sugar, Raw Equivalent	na	0
Sugar, Refined Equiv	na	0
Sunflowerseed	OilCrop	3080
Sunflowerseed Cake	OilCrop	3080
Sunflowerseed Oil	OilCrop	8840
Sweet Potatoes	Root_Tuber	920
Sweeteners, Other	na	0
Tea	MiscCrop	400
Tobacco	na	0
Tomatoes	MiscCrop	170
Vegetables, Other	MiscCrop	220

Wheat	Wheat	3340
Wine	na	0
Yams	Root_Tuber	1010

Table A.4: Mapping and Calorie Conversion for Animal Products

item	GCAM Commodity	MCal per tonne
Aquatic Animals, Others	OtherMeat_Fish	300
Aquatic Plants	na	0
Bovine Meat	Beef	1500
Butter, Ghee	Dairy	8730
Cephalopods	OtherMeat_Fish	660
Cheese	Dairy	3870
Cream	Dairy	1950
Crustaceans	OtherMeat_Fish	470
Demersal Fish	OtherMeat_Fish	420
Eggs	Poultry	1390
Fats, Animals, Raw	OtherMeat_Fish	9020
Fish Meal	OtherMeat_Fish	2620
Fish, Body Oil	OtherMeat_Fish	9020
Fish, Liver Oil	OtherMeat_Fish	9020
Freshwater Fish	OtherMeat_Fish	690
Hides and Skins	na	0
Honey	na	0
Marine Fish, Other	OtherMeat_Fish	640
Meat Meal	OtherMeat_Fish	2420
Meat, Aquatic Mammals	OtherMeat_Fish	1360
Meat, Other	OtherMeat_Fish	1260
Milk - Excluding Butter	Dairy	480
Milk, Skimmed	na	0
Milk, Whole	na	0
Molluscs, Other	OtherMeat_Fish	150
Mutton and Goat Meat	SheepGoat	2630
Offals, Edible	OtherMeat_Fish	1050
Pelagic Fish	OtherMeat_Fish	860
Pigmeat	Pork	3260
Poultry Meat	Poultry	1220
Silk	na	0
Whey	Dairy	260
Wool (Clean Eq.)	na	0

Table A.5. Crop residue biomass parameters

Item	GCAM Commodity	Harvest Index	Erosion Control	Residue Energy	Root:Shoot	Water Content

			t/Ha	GJ/t		
Almonds, with shell	MiscCrop	0.42	0.013	16.8	0.15	0.2
Anise, badian, fennel, corian.	MiscCrop	1.00	0.000	0.0	0.15	0
Apples	MiscCrop	0.85	0.019	17.3	0.15	0.8
Apricots	MiscCrop	0.68	0.034	17.3	0.15	0.8
Artichokes	MiscCrop	0.77	0.800	6.9	0.15	0.7
Asparagus	MiscCrop	0.49	1.116	6.9	0.15	0.7
Avocados	MiscCrop	0.71	0.031	6.9	0.15	0.8
Bananas	MiscCrop	0.40	0.225	6.9	0.415	0.7
Barley	OtherGrain	0.50	1.787	16.2	0.5	0.1
Beans, green	MiscCrop	0.46	1.344	6.9	0.08	0.7
Beans, dry	MiscCrop	0.46	0.000	6.9	0.08	0.24
Broad beans, horse beans, dry	MiscCrop	0.46	1.344	6.9	0.08	0.24
Cabbages and other brassicas	MiscCrop	0.80	1.349	6.9	0.15	0.7
Carrots and turnips	MiscCrop	0.53	0.986	6.9	0.15	0.8
Cashew nuts, with shell	MiscCrop	0.40	0.009	18.4	0.15	0.2
Cassava	Root_Tuber	0.38	0.886	6.9	0.15	0.1227
Cauliflowers and broccoli	MiscCrop	0.80	1.025	6.9	0.15	0.7
Cereals, nes	OtherGrain	0.40	1.030	16.5	0.15	0.05
Cherries	MiscCrop	0.85	0.225	17.3	0.15	0.8
Chestnuts	MiscCrop	0.40	0.043	18.4	0.15	0.2
Chick peas	MiscCrop	0.46	0.283	6.9	0.08	0.7
Chillies and peppers, dry	MiscCrop	0.60	0.222	6.9	0.15	0
Chillies and peppers, green	MiscCrop	0.60	2.057	6.9	0.15	0.7
Cinnamon (canella)	MiscCrop	1.00	0.000	6.9	0.15	0
Citrus fruit, nes	MiscCrop	0.93	0.004	17.3	0.15	0.8
Cloves	MiscCrop	1.00	0.000	0.0	0.15	0
Cocoa beans	MiscCrop	1.00	0.000	20.9	0.15	0
Coconuts	PalmFruit	0.66	0.627	17.3	0.15	0.8
Coffee, green	MiscCrop	1.00	0.000	20.9	0.15	0
Seed cotton	OilCrop	0.40	0.000	15.1	0.17	0.08
Cranberries	MiscCrop	1.00	0.000	6.9	0.15	0.9
Cucumbers and gherkins	MiscCrop	0.80	1.004	6.9	0.15	0.8
Currants	MiscCrop	1.00	0.000	6.9	0.15	0.8
Dates	MiscCrop	0.80	0.014	17.3	0.15	0.7
Eggplants (aubergines)	MiscCrop	0.59	2.692	6.9	0.15	0.8
Figs	MiscCrop	0.62	0.016	17.3	0.15	0.7
Fruit Fresh Nes	MiscCrop	1.00	0.000	6.9	0.15	0.7
Garlic	MiscCrop	1.00	0.000	6.9	0.15	0.7
Ginger	MiscCrop	1.00	0.000	6.9	0.15	0.7
Grapefruit (inc. pomelos)	MiscCrop	0.93	0.012	17.3	0.15	0.8
Grapes	MiscCrop	0.79	0.022	15.3	0.15	0.9
Groundnuts, with shell	OilCrop	0.40	0.871	17.7	0.07	0.09
Mangoes, mangosteens, guavas	MiscCrop	0.45	0.078	17.3	0.15	0.8
Hazelnuts, with shell	MiscCrop	0.40	0.019	18.4	0.15	0.2
Kiwi fruit	MiscCrop	0.72	0.057	17.3	0.15	0.8
Leeks, other alliaceous veg	MiscCrop	1.00	0.000	6.9	0.15	0.7
Leguminous	MiscCrop	1.00	0.000	6.9	0.15	0.7

vegetables, nes						
Lemons and limes	MiscCrop	0.95	0.008	17.3	0.15	0.8
Lentils	MiscCrop	0.61	0.143	6.9	0.15	0.2
Lettuce and chicory	MiscCrop	0.94	0.344	6.9	0.15	0.7
Linseed	OilCrop	0.26	1.671	16.2	0.15	0.15
Maize	Corn	0.53	2.754	16.9	0.18	0.13
Millet	OtherGrain	0.45	0.714	15.2	0.15	0.1
Mushrooms and truffles	MiscCrop	1.00	0.000	6.9	0.15	0
Nutmeg, mace and cardamoms	MiscCrop	1.00	0.000	0.0	0.15	0
Nuts, nes	MiscCrop	0.40	0.018	18.4	0.15	0.2
Oats	OtherGrain	0.52	1.298	16.2	0.4	0.08
Oilseeds, Nes	OilCrop	0.30	0.726	16.2	0.15	0
Olives	OilCrop	0.69	0.007	17.3	0.15	0.7
Onions (inc. shallots), green	MiscCrop	0.56	3.283	6.9	0.15	0.7
Oranges	MiscCrop	0.91	0.016	17.3	0.15	0.8
Other melons (inc.cantaloupes)	MiscCrop	0.91	0.451	6.9	0.15	0.8
Oil palm fruit	PalmFruit	0.19	0.517	17.3	0.15	0.7
Papayas	MiscCrop	0.99	0.002	17.3	0.15	0.8
Peaches and nectarines	MiscCrop	0.86	0.015	17.3	0.15	0.8
Pears	MiscCrop	0.88	0.014	17.3	0.15	0.8
Peas, dry	MiscCrop	0.30	1.066	6.9	0.08	0.1
Peas, green	MiscCrop	0.30	4.344	6.9	0.08	0.7
Pepper (Piper spp.)	MiscCrop	1.00	0.000	0.0	0.15	0
Pineapples	MiscCrop	0.26	13.844	6.9	0.15	0.8
Pistachios	MiscCrop	0.40	0.339	18.4	0.15	0.2
Plantains	MiscCrop	0.40	0.090	6.9	0.415	0.7
Plums and sloes	MiscCrop	0.80	0.010	17.3	0.15	0.8
Potatoes	Root_Tuber	0.50	0.715	6.9	0.07	0.8
Pulses, nes	MiscCrop	0.35	0.314	6.9	0.15	0.7
Pumpkins, squash and gourds	MiscCrop	0.88	0.413	6.9	0.15	0.7
Rapeseed	OilCrop	0.30	2.609	16.2	0.15	0
Raspberries	MiscCrop	1.00	0.000	6.9	0.15	0.8
Rice, paddy	Rice	0.40	0.990	13.6	0.46	0.09
Rye	OtherGrain	0.50	2.938	16.8	1.02	0.1
Sesame seed	OilCrop	0.27	0.283	16.2	0.15	0.05
Sorghum	OtherGrain	0.44	0.884	14.0	0.08	0.13
Soybeans	OilCrop	0.42	2.037	6.9	0.15	0.08
Spices, nes	MiscCrop	1.00	0.000	6.9	0.15	0
Spinach	MiscCrop	0.95	0.187	6.9	0.15	0.7
Roots and Tubers, nes	Root_Tuber	0.94	0.051	6.9	0.15	0.8
Strawberries	MiscCrop	0.45	4.010	6.9	0.15	0.8
Sugar beet	SugarCrop	0.40	1.028	6.9	0.43	0.85
Sugar cane	SugarCrop	0.70	4.679	16.6	0.18	0.3
Sunflower seed	OilCrop	0.27	1.389	6.9	0.06	0.07
Sweet potatoes	Root_Tuber	0.53	0.616	6.9	0.15	0.8
Tangerines, mandarins, clem.	MiscCrop	0.91	0.011	17.3	0.15	0.8
Tea	MiscCrop	1.00	0.000	0.0	0.15	0
Tobacco, unmanufactured	MiscCrop	1.00	0.000	6.9	0.8	0.2
Tomatoes	MiscCrop	0.33	13.793	6.9	0.14	0.95
Vanilla	MiscCrop	1.00	0.000	0.0	0.15	0
Vegetables fresh nes	MiscCrop	1.00	0.000	6.9	0.15	0
Walnuts, with shell	MiscCrop	0.40	0.036	18.4	0.15	0.2

Watermelons	MiscCrop	0.91	0.549	6.9	0.15	0.8
Wheat	Wheat	0.39	2.960	16.2	0.2	0.11
Yams	Root_Tuber	0.53	0.458	6.9	0.15	0.8

Table A.6. Sources used for parameters relevant for residue biomass and cropland vegetation carbon contents.

item	GCAM_commodity	HarvestIndex	Root:Shoot	WaterContent
Almonds, with shell	MiscCrop	Valkenburg et al. 2005	estimated	estimated
Anise, badian, fennel, corian.	MiscCrop	estimated	estimated	estimated
Apples	MiscCrop	Valkenburg et al. 2005	estimated	FAO 1994
Apricots	MiscCrop	Valkenburg et al. 2005	estimated	FAO 1994
Artichokes	MiscCrop	Valkenburg et al. 2005	estimated	estimated
Asparagus	MiscCrop	Valkenburg et al. 2005	estimated	estimated
Avocados	MiscCrop	Valkenburg et al. 2005	estimated	FAO 1994
Bananas	MiscCrop	Srinivas et al. 2005	zum Felde et al. 2003	FAO 1994
Barley	OtherGrain	West 2011	West 2011	West 2011
Beans, green	MiscCrop	West 2011	West 2011	estimated
Beans, dry	MiscCrop	West 2011	West 2011	West 2011
Broad beans, horse beans, dry	MiscCrop	West 2011	West 2011	West 2011
Cabbages and other brassicas	MiscCrop	EPIC model	estimated	estimated
Carrots and turnips	MiscCrop	EPIC model	estimated	estimated
Cashew nuts, with shell	MiscCrop	Valkenburg et al. 2005	estimated	estimated
Cassava	Root_Tuber	Purdue 2007	estimated	Pongsawatmanita et al. 2002
Cauliflowers and broccoli	MiscCrop	EPIC model	estimated	estimated
Cereals, nes	OtherGrain	EPIC model	estimated	estimated
Cherries	MiscCrop	Valkenburg et al. 2005	estimated	FAO 1994
Chestnuts	MiscCrop	Valkenburg et al. 2005	estimated	estimated
Chick peas	MiscCrop	West 2011	West 2011	estimated
Chillies and peppers, dry	MiscCrop	EPIC model	estimated	estimated
Chillies and peppers, green	MiscCrop	EPIC model	estimated	estimated
Cinnamon (canella)	MiscCrop	estimated	estimated	estimated
Citrus fruit, nes	MiscCrop	estimated	estimated	FAO 1994
Cloves	MiscCrop	estimated	estimated	estimated
Cocoa beans	MiscCrop	estimated	estimated	estimated
Coconuts	PalmFruit	Mialet-Serra et al. 2005	estimated	estimated
Coffee, green	MiscCrop	estimated	estimated	estimated
Seed cotton	OilCrop	West 2011	West 2011	West 2011
Cranberries	MiscCrop	estimated	estimated	FAO 1994
Cucumbers and gherkins	MiscCrop	Valkenburg et al. 2005	estimated	FAO 1994
Currants	MiscCrop	estimated	estimated	FAO 1994
Dates	MiscCrop	Valkenburg et al. 2005	estimated	FAO 1994
Eggplants (aubergines)	MiscCrop	EPIC model	estimated	estimated
Figs	MiscCrop	Valkenburg et al. 2005	estimated	FAO 1994

Fruit Fresh Nes	MiscCrop	estimated	estimated	FAO 1994
Garlic	MiscCrop	estimated	estimated	estimated
Ginger	MiscCrop	estimated	estimated	estimated
Grapefruit (inc. pomelos)	MiscCrop	Valkenburg et al. 2005	estimated	FAO 1994
Grapes	MiscCrop	Valkenburg et al. 2005	estimated	FAO 1994
Groundnuts, with shell	OilCrop	West 2011	West 2011	West 2011
Mangoes, mangosteens, guavas	MiscCrop	estimated	estimated	FAO 1994
Hazelnuts, with shell	MiscCrop	estimated	estimated	estimated
Kiwi fruit	MiscCrop	Valkenburg et al. 2005	estimated	FAO 1994
Leeks, other alliaceous veg	MiscCrop	estimated	estimated	estimated
Leguminous vegetables, nes	MiscCrop	estimated	estimated	estimated
Lemons and limes	MiscCrop	Valkenburg et al. 2005	estimated	estimated
Lentils	MiscCrop	EPIC model	estimated	estimated
Lettuce and chicory	MiscCrop	Valkenburg et al. 2005	estimated	estimated
Linseed	OilCrop	Mondal et al. 2005	estimated	estimated
Maize	Corn	West 2011	West 2011	West 2011
Millet	OtherGrain	Roth et al. 2000	estimated	estimated
Mushrooms and truffles	MiscCrop	estimated	estimated	estimated
Nutmeg, mace and cardamoms	MiscCrop	estimated	estimated	estimated
Nuts, nes	MiscCrop	Valkenburg et al. 2005	estimated	estimated
Oats	OtherGrain	West 2011	West 2011	West 2011
Oilseeds, Nes	OilCrop	EPIC model	estimated	estimated
Olives	OilCrop	Valkenburg et al. 2005	estimated	estimated
Onions (inc. shallots), green	MiscCrop	EPIC model	estimated	estimated
Oranges	MiscCrop	Valkenburg et al. 2005	estimated	FAO 1994
Other melons (inc.cantaloupes)	MiscCrop	Valkenburg et al. 2005	estimated	estimated
Oil palm fruit	PalmFruit	Wahid et al. 2004	estimated	estimated
Papayas	MiscCrop	estimated	estimated	FAO 1994
Peaches and nectarines	MiscCrop	Valkenburg et al. 2005	estimated	FAO 1994
Pears	MiscCrop	Valkenburg et al. 2005	estimated	FAO 1994
Peas, dry	MiscCrop	EPIC model	estimated	estimated
Peas, green	MiscCrop	EPIC model	estimated	estimated
Pepper (Piper spp.)	MiscCrop	estimated	estimated	estimated
Pineapples	MiscCrop	Bhattacharyya et al. 1992	estimated	FAO 1994
Pistachios	MiscCrop	Valkenburg et al. 2005	estimated	estimated
Plantains	MiscCrop	Srinivas et al. 2005	zum Felde et al. 2003	FAO 1994
Plums and sloes	MiscCrop	Valkenburg et al. 2005	estimated	FAO 1994
Potatoes	Root_Tuber	West 2011	West 2011	West 2011
Pulses, nes	MiscCrop	EPIC model	estimated	estimated
Pumpkins, squash and gourds	MiscCrop	Valkenburg et al. 2005	estimated	estimated

Rapeseed	OilCrop	EPIC model	estimated	estimated
Raspberries	MiscCrop	estimated	estimated	FAO 1994
Rice, paddy	Rice	West 2011	West 2011	West 2011
Rye	OtherGrain	West 2011	West 2011	West 2011
Sesame seed	OilCrop	Hay 1995	estimated	estimated
Sorghum	OtherGrain	West 2011	West 2011	West 2011
Soybeans	OilCrop	West 2011	West 2011	West 2011
Spices, nes	MiscCrop	estimated	estimated	estimated
Spinach	MiscCrop	EPIC model	estimated	estimated
Roots and Tubers, nes	Root_Tuber	EPIC model	estimated	estimated
Strawberries	MiscCrop	EPIC model	estimated	FAO 1994
Sugar beet	SugarCrop	West 2011	West 2011	West 2011
Sugar cane	SugarCrop	West 2011	West 2011	West 2011
Sunflower seed	OilCrop	West 2011	West 2011	West 2011
Sweet potatoes	Root_Tuber	EPIC model	estimated	estimated
Tangerines, mandarins, clem.	MiscCrop	Valkenburg et al. 2005	estimated	FAO 1994
Tea	MiscCrop	estimated	estimated	estimated
Tobacco, unmanufactured	MiscCrop	estimated	estimated	estimated
Tomatoes	MiscCrop	EPIC model	Choi et al. 1997	estimated
Vanilla	MiscCrop	estimated	estimated	estimated
Vegetables fresh nes	MiscCrop	estimated	estimated	estimated
Walnuts, with shell	MiscCrop	Valkenburg et al. 2005	estimated	estimated
Watermelons	MiscCrop	Valkenburg et al. 2005	estimated	estimated
Wheat	Wheat	West 2011	West 2011	West 2011
Yams	Root_Tuber	EPIC model	estimated	estimated