***Supplemental Information***

1. **Definitions of Land Use Change**

Land use chance (LUC) is set into motion through direct and indirect causal relationships. Global LUC includes direct and indirect LUC (dLUC and iLUC), which are overlapping phenomena defined as follows:

* Biofuel-induced dLUC is caused by growing biofuel crops on land previously used for a different purpose (e.g., agricultural, forestry, pristine land). Greenhouse gas (GHG) emissions from dLUC depend on site-specific conditions such as soil type, local climate, and food and bioenergy crop management practices. Despite uncertainties, dLUC can be quantified with sufficient confidence that there is considerable consensus about its use for policy guidance (e.g., Gibbs *et al* 2008).

Biofuel-induced iLUC is caused by biofuel feedstock production displacing other crops and market responses that spur compensating production elsewhere. When biofuel feedstock cultivation replaces the original crops, the price of those original crops increases due to the decline in supply, prompting increased production of those or substitute crops in another region or country. iLUC remains a contentious policy issue because of uncertainty in estimation, as outlined in the main paper.

1. **System Dynamics**

System dynamics (SD) can be characterized as an analytical framework for understanding and improving the performance dynamic of systems and processes that are feedback-rich. It was developed in the 1950s at MIT as an extension of feedback-control-system principles to the analysis of production and distribution systems. Throughout its history, the framework has been applied to a broad range of issues in business, government, non-profit, and academic settings. Many of these uses described are noted in *Business Dynamics: Systems Thinking and Modeling for a Complex World* (Sterman 2000), which focuses on business and policy applications.

A central theme in (SD) applications is the graphical representation of a system’s feedback structure using stocks and flows (see figure S1 for a simple stock-flow diagram). Stocks represent accumulation processes, while flows represent the rates of change over time which build or deplete stocks. Stocks depict the state variables within a system, while flows represent time derivatives.



Stock(t) = Stock (t-dt) + (flow)\*dt

Flow = stock \* k

k = constant

dt = simulation solution interval

**Figure S1**. An SD representation of a very simple feedback mechanism or controller. The cloud symbol indicates the system boundary.

Mathematically, the structure of a formal model corresponding to a system dynamics diagram comprises a system of coupled, nonlinear, first-order differential equations. These are typically implemented in system dynamics software tools as first-order difference equations, and simulation is accomplished through use of standard numerical methods.

For many real-world feedback-rich systems, change unfolds over time in response to human decisions and institutional actors within the system. An important common characteristic of system dynamics models is their focus on transparent representation of decision rules that drive actions. In many instances (such as the Biomass Scenario Model described elsewhere in this special issue), decisions are depicted as economic in nature, responding to and subsequently influencing endogenously-generated market dynamics. In other instances, such as the LUC described here, decisions are represented at a highly aggregated level without representing pricing dynamics explicitly.

One productive use of system dynamics is to create “virtual worlds” in which policies and scenarios are tested in a simulation model of the real system. The potential of virtual worlds to underwrite learning and insight is great in settings characterized by a high degree of dynamic complexity (Sterman 2006). The learning process is an iterative one, in which discrepancies among individual mental models, formal simulation models, and data can identify weaknesses and areas for improvement in each arena (Homer 1996).

System dynamics has long been used to approach global social-economic-system (SES) issues. For example, *World Dynamics* (Forrester 1971) and *Limits to Growth* (Meadows 1972 and Meadows 2004 update) represent early (and highly debated) efforts to generate scenarios around the dynamic interplay of population, food, industry, and natural resources. More recently, system dynamics has been used to support inquiry into global climate change dynamics. For example, Climate Interactive is an non-government organizationGO working to build a community that “creates, shares, and uses credible models, accessible simulations, and related media in order to improve the way leaders and citizens around the world think about the climate” (<http://climateinteractive.org/simulations>). Their simulations are based on SD models of energy-climate interactions.

1. **BioLUC Modeling Data and Assumptions**

The model’s land use categories are based on aggregated and calculated FAO land use estimates. The specific FAO categories we utilize are *Arable Land*, *Permanent Crops*, *Permanent Meadows and Pastures*, and *Forest Area*. Crop categories derived from the FAO categories are *Cropland*, *Pasture Land*,and *Available Land* (table S1), and initial land stocks for 1991 for primary land categories are shown in figure S2. It is necessary to disaggregate the FAO Arable Land category into Cropland and Pastureland categories, because as Arable Land is defined by FAO as being composed of land under “temporary agricultural crops” as well as “temporary meadows for mowing or pasture,” (FAO 2010b). Land categories such as forest area include land whether or not it is protected.

BioLUC’s land use categories are based on aggregated and calculated FAO land use estimates:

* BioLUC Available Forest Land = FAO Forest Area
* BioLUC Cropland – (Cropland regional share) \*(FAO Arable Land) where regional share is 0.95 for ROW and 0.86 for US (FAO 2010a, Holmgren 2006)
* BioLUC Pastureland = (Pasture regional share) \* (FAO Arable Land) where regional share is 0.05 for ROW and 0.14 for the US
* Cropland regional share = FAO Permanent Crops for region/FAO Arable Land for region

Other land is not considered directly in this version of BioLUC due to ambiguities and data concerns (Matthews 2001).

Initial land stocks and rates of land abandonment, where cropland is used so intensively that it must be abandoned, are taken from global studies and applied equally to global and US regions (Campbell *et al* 2008). Land abandonment rates are calculated based on existing cropland and retain a constant rate throughout the model analysis. Rates of land restoration, where abandoned agricultural land returns to Available Land, are taken from Houghton *et al* (2000). Fallow land estimates are taken from FAO for the US region in 2002 and from Siebert *et al* (2010)for the global region. Fallow land remains a constant percentage of total cropland throughout the model analysis.

**Table S1.** Land use and animal product categories used in BioLUC.

|  |  |  |  |
| --- | --- | --- | --- |
| Available Land | Forest |  |  |
| Grassland |  |  |
| Pastureland | Formerly Forest |  |  |
| Formerly Pasture |  |  |
| Cropland | Formerly Forest or Pasture | Fallow |  |
| Forage |  |
| Fiber | Vegetable/Fruit/Nut | Other | |
| Commodity Crops | Maize |
| Wheat |
| Rice |
| Grains Not Elsewhere Classified |
| Oil Crops |
| Sugar |
| Energy Crops | |
|  | Sugar |
| Energy Crops |  |
| Abandoned | Formerly Forest |  |  |
| Formerly Pasture |  |  |

**Figure S2**. Initial land stocks in 1991.

In the model, cropland and pastureland taken out of production will revert back to either forest or pastureland, depending on local climate. The percentage of cropland and pastureland that reverts to forest or pasture remains constant throughout the duration of the study period and is derived from global and North American estimates discussed in Cha (1997). The real-world process of land reverting to forest and/or pasture would not return land to the exact characteristics of the prior land category. The longer-term effects of land conversion, abandonment, and reversion are outside the dynamics of this model, even though they could lead to long-term changes in biodiversity and soil structure. Data on deforestation and forest carbon stocks are from the FAO Forest Resource Assessment (FAO 2010a). The details of future forest management practices are below the resolution of BioLUC.

FAOSTAT (2010b) datasets are used to populate most SD model variables up to the present; they are based on statistics for area harvested, production quantity, and biomass yields through 2010. Crop data were aggregated into eight crop categories, plus an “other crop” category, which is only used as a catch-all for many non-food agricultural products not relevant for this analysis. In addition, any data that could cause double-counting of production quantity or area harvested was excluded, such as derivative byproducts of main commodity crops. For the US region, data were taken from the FAOSTAT (2010a) US category. The ROW region data were calculated as the difference between FAO World and US categories.

Inputs to the model for commodity yields from FAOSTAT and Alexandratos and Bruinsma (2012) are shown in table S2. To obtain yearly yield data we assume a linear trend for crop yields and interpolate between present yields, 2030 yields, and 2050 yields from from Alexandratos and Bruinsma (2012) for the different crop categories for 2030 and 2050. Outside the indirect effects of the improvements in yields of these commodities, no meat specific yield improvements are assumed (e.g., land-use-intensification).

**Table S2**. Commodity yields used across all scenarios from 1991-2050 in Mg/harvested ha/year. These yields are used for used for both food commodities and food-based biofuels.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Location** | **Commodity Type** | **1991** | **2000** | **2010** | **2020** | **2030** | **2040** | **2050** |
| ROW | maize | 2.9 | 3.3 | 3.8 | 4.1 | 4.4 | 4.7 | 5.0 |
| wheat | 2.2 | 2.6 | 2.9 | 3.1 | 3.3 | 3.6 | 3.8 |
| rice | 3.3 | 3.7 | 4.1 | 4.4 | 4.7 | 5.0 | 5.3 |
| other cereals | 1.4 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.2 |
| oils (from crops) | 1.7 | 1.9 | 2.1 | 2.3 | 2.5 | 2.7 | 2.9 |
| sugar | 62 | 65 | 71 | 79 | 88 | 96 | 104 |
| vegetable, fruit, and nuts | 0.9 | 0.9 | 1.0 | 1.2 | 1.4 | 1.6 | 1.7 |
| USA | maize | 5.1 | 5.8 | 6.3 | 6.6 | 6.9 | 7.2 | 7.4 |
| wheat | 2.3 | 2.6 | 2.9 | 3.1 | 3.2 | 3.4 | 3.6 |
| rice | 3.4 | 3.8 | 4.2 | 4.5 | 4.8 | 5.1 | 5.4 |
| other cereals | 1.4 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.2 |
| oils (from crops) | 1.7 | 1.9 | 2.1 | 2.3 | 2.5 | 2.7 | 2.9 |
| sugar | 62 | 65 | 71 | 79 | 88 | 96 | 104 |
| vegetable, fruit, and nuts | 0.9 | 0.9 | 1.0 | 1.2 | 1.4 | 1.6 | 1.7 |

The production of meat and its implicit demand for biomass (i.e., land) is a primary determinant of LUC. The meat categories used in BioLUC are based on FAO meat and animal product categories (FAO 2010b). The FAO animal product categories are aggregated into four animal product categories in BioLUC, based on similarities in production practices and inputs.

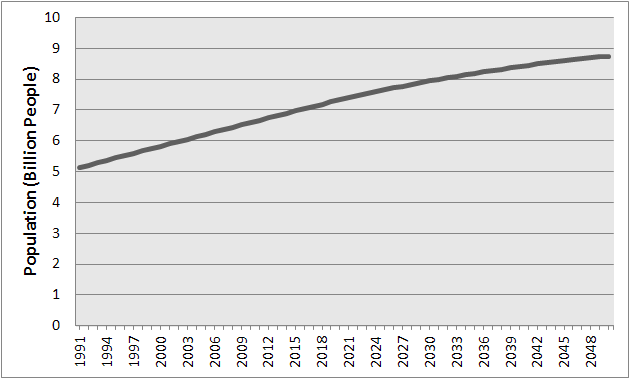
Table 3 in the main paper presents the meat input/output tables used to derive land base (biomass) demands as a result of finished meat demand; all meat demands are based on “finished” meat, which excludes meat waste material such as bones and entrails. Two types of production systems are considered in this model: intensive (US) and extensive (ROW). Data used for the intensive production input/output table are taken preferentially from LCA studies and include the feed required to maintain a herd (e.g., beef, goat, and sheep); a gestating/lactating mother and offspring (pig); and an egg-producing hen house (poultry). Please refer to Pelletier (2008), Pelletier *et al* (2009), and Pelletier *et al* (2010) for more specific information on specific systems’ boundaries and assumptions for each. There is a dearth of US-specific dairy LCA data; therefore, the dairy input/output is based on a report by Rotz and Zartman (1997) and is not on a life cycle basis.

**Table 3**. Mass (kg) of Specific Crop Products Required to Produce a Mass of Finished Meat Product. The system represented is an intensive meat production system **(**Pelletier 2008, Pelletier *et al* 2009, Pelletier *et al* 2010, Rotz and Zartman 1997).

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Meat Class** | **Forage** | **Pasture** | **Maize** | **Wheat** | **Rice** | **Cereal**  **Grain NEC** | **Oil Crop** | **Sugar** | **Total** |
| Beef, Goat, Sheep | 6.1 | 4.9 | 2.6 | 0.1 | 0.0 | 0.0 | 1.1 | 0.0 | 14.8 |
| Dairy | 4.5 | 0.0 | 1.2 | 0.0 | 0.0 | 2.0 | 0.0 | 0.0 | 7.7 |
| Pig | 0.0 | 0.0 | 1.2 | 1.4 | 0.0 | 0.3 | 0.7 | 0.0 | 3.6 |
| Poultry | 0.0 | 0.0 | 1.4 | 0.3 | 0.0 | 0.0 | 0.6 | 0.0 | 2.4 |

The crops/land production inputs for meat production found in the literature are aligned with categories in the rest of the model. However, FAOSTAT inputs do not align with the LUC model categories. Therefore, the data are aggregated from the original sources to fit into the categories used herein. The extensive beef, goat, and sheep production system is based on Pelletier *et al* (2009). The production of pig and dairy for the ROW case is assumed to be the same for the US case. Extensive poultry production is assumed to occur without biomass input; in an extensive “free range” poultry production system, the animals are assumed to feed primarily on insects.

Global population assumptions used over the course of running the BioLUC model from 1991-2050 are shown in figure S3. Population estimates reflect FAO’s PopSTAT sheet which is part of the FAOSTAT data (2010b).



**Figure S3.** Global population assumptions from 1991 to 2050.

1. **Scenario-Based Inputs**

The lower food demand level for the BAU and HB scenarios is developed from projections of per-capita demand for commodity crops (Alexandratos and Bruinsma 2012) and shown in table S3. These data are grouped into categories of “Developed countries” and “Developing countries.” Using correspondence tables within the report, we assign world regions to these categories and aggregate the data into our model regions, US and ROW. Per-capita commodity crop demand levels are provided for years 2006, 2030, and 2050. Data are assumed to be linear between provided years and are interpolated for every year in between. Per-capita food demand for animal products is provided for 2006, and growth rates in consumption of animal products are also provided for time periods 1991-2006 and 2006-2050. Using consumption growth rates, we are able to generate per-capita animal product demand levels for all years in the model. Additional scaling factors for food wastage and inefficiencies in the system (e.g., spoilage during storage and transportation) are not necessary, as these factors are already taken into account within Alexandratos and Bruinsma’s (2012) data.

**Table S3**.BAU and HB scenario food commodity demand from 1991-2050 in kg/capita-yr.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Location** | **Commodity Type** | **1991** | **2000** | **2010** | **2020** | **2030** | **2040** | **2050** |
| ROW | cow/sheep/goat-like meat | 11 | 11 | 11 | 11 | 11 | 12 | 12 |
| dairy | 70 | 74 | 79 | 83 | 87 | 90 | 94 |
| pig-like meat | 13 | 14 | 15 | 15 | 16 | 16 | 17 |
| poultry-like meat | 7.0 | 9.1 | 12 | 13 | 14 | 16 | 18 |
| maize | 37 | 36 | 37 | 39 | 42 | 42 | 42 |
| wheat | 53 | 52 | 51 | 50 | 49 | 49 | 49 |
| rice | 38 | 37 | 36 | 35 | 34 | 34 | 34 |
| other cereals | 33 | 32 | 32 | 33 | 34 | 34 | 34 |
| oils (from crops) | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| sugar | 22 | 21 | 22 | 22 | 23 | 24 | 25 |
| vegetables, fruits, and nuts | 73 | 74 | 76 | 78 | 81 | 83 | 85 |
| USA | cow/sheep/goat-like meat | 26 | 25 | 24 | 24 | 25 | 25 | 25 |
| dairy | 201 | 202 | 204 | 210 | 215 | 219 | 222 |
| pig-like meat | 31 | 32 | 33 | 33 | 34 | 34 | 35 |
| poultry-like meat | 19 | 22 | 25 | 27 | 29 | 31 | 33 |
| maize | 37 | 38 | 39 | 42 | 44 | 44 | 44 |
| wheat | 53 | 54 | 54 | 53 | 51 | 51 | 51 |
| rice | 38 | 39 | 39 | 37 | 35 | 35 | 35 |
| other cereals | 33 | 34 | 35 | 35 | 36 | 36 | 36 |
| oils (from crops) | 16 | 18 | 19 | 20 | 20 | 21 | 21 |
| sugar | 36 | 35 | 34 | 33 | 33 | 33 | 33 |
| vegetables, fruits, and nuts | 81 | 80 | 79 | 78 | 76 | 76 | 75 |

To obtain the higher food demand level applied in the HF and (HFB scenarios, we apply Tilman et al. (2011) per capita demand projected increases from 2005 to 2050 to the lower food demand level, as shown in table S4. We assume Tilman et al.’s (2011) per capita food demand increase (~40%) and adjust it to the Alexandratos and Bruinsma (2012) assumptions to maintain the basic trends of the original low food demand scenario, but emphasize the effects exaggerating pre-existing demand trends. Tilman et al. (2012) does not specified how the demand increase is distributed across individual food categories. We closely approximate the 40% increase by equally applying changes across all commodities through a ~45% increase in annual growth of each commodity starting in 2010 relative to the low food demand scenario.

**Table S4**. HF and HFB scenario food commodity demand from 1991-2050 in kg/capita-yr.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Location** | **Commodity Type** | **1991** | **2000** | **2010** | **2020** | **2030** | **2040** | **2050** |
| ROW | cow/sheep/goat like meat | 11 | 11 | 11 | 13 | 14 | 16 | 18 |
| diary | 70 | 74 | 83 | 95 | 107 | 118 | 129 |
| pig like meat | 13 | 14 | 16 | 17 | 19 | 21 | 23 |
| poultry like meat | 7.0 | 9.1 | 13 | 16 | 20 | 25 | 31 |
| maize | 37 | 36 | 39 | 45 | 52 | 52 | 54 |
| wheat | 53 | 52 | 52 | 53 | 54 | 54 | 55 |
| rice | 38 | 37 | 37 | 38 | 38 | 39 | 39 |
| other cereals | 33 | 32 | 33 | 36 | 39 | 39 | 40 |
| oils (from crops) | 10 | 11 | 13 | 16 | 18 | 21 | 23 |
| sugar | 22 | 21 | 22 | 25 | 27 | 30 | 32 |
| vegetable, fruit, and nuts | 73 | 74 | 77 | 81 | 88 | 93 | 97 |
| USA | cow/sheep/goat like meat | 26 | 25 | 25 | 25 | 25 | 25 | 25 |
| diary | 201 | 202 | 207 | 221 | 234 | 243 | 251 |
| pig like meat | 31 | 32 | 34 | 34 | 35 | 36 | 37 |
| poultry like meat | 19 | 22 | 27 | 31 | 36 | 41 | 46 |
| maize | 37 | 38 | 41 | 46 | 52 | 52 | 52 |
| wheat | 53 | 54 | 56 | 56 | 57 | 57 | 57 |
| rice | 38 | 39 | 40 | 40 | 41 | 41 | 41 |
| other cereals | 33 | 34 | 35 | 37 | 39 | 39 | 39 |
| oils (from crops) | 16 | 18 | 20 | 21 | 22 | 23 | 24 |
| sugar | 36 | 35 | 34 | 34 | 35 | 35 | 35 |
| vegetable, fruit, and nuts | 81 | 80 | 80 | 81 | 82 | 82 | 82 |

We mostly follow Alexandratos and Bruinsma (2012) for the lower biofuels demand level used in BAU and HF scenarios, and convert these demands to energy and land requirements as listed in tables S5 and S6. Alexandratos and Bruinsma (2012) use “OECD-FAO Agricultural Outlook 2010-2019” (OECD-FAO 2010) biofuel production projections for ethanol and biodiesel in 2019. For all following years, production is assumed to level off at the projected 2019 values. US Energy Information Administration (EIA) spreadsheets for ethanol and biodiesel production are used for years prior to 2008 (EIA 2012).

From 2008 to 2019, ethanol and biodiesel production are assumed to increase linearly--from 2008 historical data to the World Agricultural Outlook values for 2019. USA region data is taken from US ethanol and biodiesel production in the spreadsheet, while ROW region data is the difference between provided world biofuel production and US values. Alexandratos and Bruinsma (2012) presume that only food-based crop biofuels are available to meet policy requirements despite cellulosic ethanol requirements (US EPA 2010). The amended scenario assumes the mandated 57 billion dm3 of corn ethanol and about 32 billion dm3 of cellulosic ethanol by 2019.

To calculate the land and energy requirements, we used biodiesel conversion and oil yield assumptions for palm and soybeans from the Biomass Scenario Model (NREL 2012). The details of markets are below the resolution of the BioLUC model. To calculate land requirements solely for biofuels and not co-products, we assumed economic co-product allocation from Hoefnagels *et al* (2010) which was generally the most conservative (i.e., with regards to assuming higher land requirements for the biofuel).

Cellulosic ethanol yield assumptions from 2020-2050 based on US DOE 2011 for the USA and two papers by Hacatoglu et al. (2011) and Djomo et al. (2011) for the ROW are reported in Table S7. Approximately 100% cellulosic ethanol from herbaceous feedstocks was assumed for the US (US DOE 2011). We assumed a mixture of 70% woody and 30% herbaceous crop feedstocks based on lower yield estimates in Djomo et al. (2011) and Hacatoglu et al. (2011) for the ROW. In the US a 1% improvement in yield per year is assumed (US DOE 2011). The same improvement is extended to the ROW. ROW cellulosic ethanol yields are only used in the higher biofuel (HB) demand scenario.

**Table S5**. BAU and HF biofuel energy demand from 1991-2050 in EJ/yr.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Location** | **Commodity Type** | **1991** | **2000** | **2010** | **2020** | **2030** | **2040** | **2050** |
| USA | ethanol | 0.02 | 0.21 | 1.4 | 2.3 | 2.3 | 2.3 | 2.3 |
| biodiesel | 0.00 | 0.00 | 0.10 | 0.14 | 0.14 | 0.14 | 0.14 |
| ROW | ethanol | 0.04 | 0.38 | 1.7 | 3.1 | 3.1 | 3.1 | 3.1 |
| biodiesel | 0.00 | 0.03 | 0.65 | 1.4 | 1.4 | 1.4 | 1.4 |

**Table S6**. BAU and HF land demand from 1991-2050 in million ha/yr.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Location** | **Commodity Type** | **1991** | **2000** | **2010** | **2020** | **2030** | **2040** | **2050** |
| USA | ethanol | 0.26 | 2.3 | 14 | 22 | 22 | 21 | 20 |
| biodiesel | 0 | 0 | 1.9 | 2.6 | 2.4 | 2.2 | 2.1 |
| ROW | ethanol | 0.64 | 5.7 | 18 | 34 | 31 | 29 | 28 |
| biodiesel | 0.14 | 1.2 | 22 | 43 | 39 | 36 | 34 |

**Table S7.** HB and HFB cellulosic biofuel yields from 1991-2050 in Mg/harvest ha/yr.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Region** | **Yearly Yield Increase** | **2020** | **2030** | **2040** | **2050** |
| USA | 1% (Base) | 16 | 17 | 19 | 21 |
| ROW | 1% (Base) | 11 | 12 | 13 | 14 |

The HB demand level takes projections for world gasoline and diesel demand in 2050 and assumes 25% displacement of this demand by biofuels. US Energy Information Administration (EIA) historic data for gasoline and diesel production from 1990 to 2008 (IPAA 2012) is used to create an auto-regressive model, projecting world gasoline and diesel demand out to 2050. We assume world biofuel demand increases linearly from 2010 EIA ethanol and renewable diesel production data to the projected 25% displacement in 2050, which in addition to the food crop-based biofuel demands in the low biofuel demand scenario. Additional biofuel demands are assumed to be met only by cellulosic ethanol and renewable diesel. World biofuel demand is allocated to US and ROW regions in proportion to 2010 ratios. Resulting energy demands for biofuels from 1991-2050 are shown in table S8.

Harvested area for cellulosic ethanol and renewable diesel were calculated and listed in table S9 based on the cellulosic feedstock yields in table S9, cellulosic ethanol conversion yields (NREL 2012), and renewable diesel conversion yields which are only slightly higher than biodiesel (NREL 2012).

**Table S8.** HB and HFB land demand from 1991-2050 in EJ/yr.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Location** | **Commodity Type** | **1991** | **2000** | **2010** | **2020** | **2030** | **2040** | **2050** |
| USA | ethanol | 0.02 | 0.21 | 1.4 | 2.7 | 6.1 | 9 | 13 |
| biodiesel/renewable diesel | 0 | 0 | 0.10 | 0.18 | 0.60 | 1.0 | 1.4 |
| ROW | ethanol | 0.04 | 0.38 | 1.7 | 3.3 | 5.4 | 7.5 | 9.6 |
| biodiesel/renewable diesel | 0.00 | 0.03 | 0.65 | 2.1 | 9 | 16 | 23 |

**Table S9.** HB and HFB land demand from 1991-2050 in million ha/yr.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Location** | **Commodity Type** | **1991** | **2000** | **2010** | **2020** | **2030** | **2040** | **2050** |
| USA | ethanol | 0.26 | 2.3 | 14 | 24 | 40 | 53 | 63 |
| biodiesel/renewable diesel | 0 | 0 | 1.9 | 3.4 | 10 | 16 | 21 |
| ROW | ethanol | 0.64 | 5.7 | 18 | 38 | 49 | 58 | 65 |
| biodiesel/renewable diesel | 0.14 | 1.2 | 22 | 63 | 250 | 408 | 543 |

**Alternative Cellulosic Yield Assumptions**

A major limitation of our analysis is that we used aggregated average yields encompassing a wide regional variability and only examine one potential future for the yields agricultural commodities. Potential future yields are uncertain and likely more variable than implied in this analysis due to factors such as:

* Climate change and related extreme weather events, such as drought.
* Price responses in our high demand scenarios, such as intensification of the use of land or investment in agricultural research and development.
* Alternative bioenergy technology and feedstock systems, other than those used in our projections.

Consideration of alternative future yields would likely not have a major impact on the underlying dynamics evaluated in our results. However, to better understand LUC drivers, it is important to at least understand the potential magnitude of the effects of alternative average yields on future food and fuel conditions. The exploration of adding sophisticated model structure, allowing intensification of yields within the model, is beyond the scope of this analysis, but is a potential future option for the BioLUC model.

We calculated alternative cellulosic biofuel land requirements based on higher and lower assumptions about improvements in yield overtime. A 1.5% and 0.5% growth in average yield per year for cellulosic feedstocks was used for high and low cases, respectively, as shown in table S10. Using these alternative yield scenarios, land demand for overall biofuel production was recalculated and is shown in table S11. The difference in global yearly land demand is about +/- 12.5 million ha per year by 2050 when high and low yield scenarios are compared to the “base case”. The “base case” represents only a 1% increase in average yield per year of cellulosic feedstocks.

The difference between land required in the high and low alternative scenarios and the base case was calculated in terms of potential additional food demands that could or could not be met to more clearly illustrate the practical impacts of different future yields. The results of these calculations are shown in table S12 in the form of the number of people per year whose demand, as projected by Alexandratos and Bruinsma (2012), is met. Results indicate that shifting yields of a biofuel stream of about 15 EJ/year by half a percent could use an amount of land equivalent to that needed to meet projected wheat demand of 0.4-0.5 billion people for 2050 (i.e., see Table S3 for wheat demand). Future yield assumptions are an important driver of the magnitude of the land in use by biofuels and other agricultural commodities for human uses.

**Table S10.** High and lowcellulosic feedstock yields assumptions from 2020-2050 in Mg/harvest ha-yr. The high and low yield assumptions are 1.5% and 0.5% yearly growth rates, respectively.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Region** | **Yearly Yield Increase** | **2020** | **2030** | **2040** | **2050** |
| USA | 1.5% (High) | 16 | 19 | 22 | 25 |
| ROW | 1.5% (High) | 11 | 13 | 15 | 17 |
| USA | 0.5% (Low) | 15 | 16 | 17 | 18 |
| ROW | 0.5% (Low) | 10 | 11 | 11 | 12 |

**Table S11.** Land demand from 2020-2050 in million ha/yr using baseline, high, and low cellulosic feedstock yield assumptions.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Region** | **Yearly Yield Increase** | **2020** | **2030** | **2040** | **2050** |
| USA | 1% (Base) | 50 | 67 | 81 | 93 |
| ROW | 1% (Base) | 222 | 371 | 496 | 604 |
| USA | 1.5% (High) | 50 | 66 | 78 | 87 |
| ROW | 1.5% (High) | 222 | 370 | 493 | 598 |
| USA | 0.5% (Low) | 50 | 68 | 85 | 100 |
| ROW | 0.5% (Low) | 222 | 372 | 500 | 610 |

**Table S12.** Difference in land demand in the high and low cellulosic feedstock yield scenarios relative to the baseline case from 2020-2050. The difference in land demand is presented in terms of annual wheat demand of 1 million people (Alexandratos and Bruinsma 2012).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Region** | **Yearly Yield Increase** | **2020** | **2030** | **2040** | **2050** |
| USA | 1.5% (High) | 3 | 75 | 217 | 413 |
| ROW | 1.5% (High) | 0 | 83 | 242 | 462 |
| USA | 0.5% (Low) | -3 | -81 | -247 | -496 |
| ROW | 0.5% (Low) | 0 | -88 | -269 | -539 |

1. **Next BioLUC Analysis Steps**

The two-region structure of the BioLUC model used in this study is designed to be a stable first step in the model’s development. Efforts are underway to expand BioLUC to include additional regions. Future versions of BioLUC are planned to model 19 regions, parallel to GTAP, which will facilitate input data development and comparative analysis. We are interested in expanding such cross-comparison analysis to include other land use modeling systems (e.g., GCAM) (Joint Global Change Research Institute 2012). The BioLUC model will be publicly released once expanded to 19 regions so that other researchers can run their own scenarios. We are also plan additional analyses of a wide variety of scenarios based on important alternatives raised in the extensive LUC literature, which we continue to review

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