Joint Working Party on Agriculture and the Environment

GREENHOUSE GAS ACCOUNTING: LIFE CYCLE ANALYSIS OF BIOFUELS AND LAND USE CHANGE

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GREENHOUSE GAS ACCOUNTING:
LIFE CYCLE ANALYSIS OF BIOFUELS AND LAND USE CHANGE

John A. Miranowski¹,²

1. Introduction

1. Increasing attention is being directed to observed increases in levels of atmospheric carbon dioxide (CO₂), potential implications for climate change, and the signing of the United Nations Framework Convention on Climate Change (UNFCCC). According to Jonas et al. (1999) and Solomon et al. (2009), atmospheric CO₂ levels have increased from approximately 280 ppm (parts-per-million, 10⁻⁶) in 1800 to 365 ppm in 1999, to near 385 ppm in 2008. In response to adverse effects from the threat of a human-induced change in the Earth’s climate, the UNFCCC was adopted in 1992 and came into force in 1994. The convention has strongly encouraged nations to assess their contributions to sources and sinks of CO₂ and to evaluate the processes that control CO₂ and other gas accumulations in the atmosphere.

2. Agriculture and forestry activities play a key role in the atmospheric levels of anthropogenic greenhouse gas (GHG) emissions, and depending on agriculture and forestry practices, these activities can either contribute to the reduction or the atmospheric build-up of GHG emissions. In 2007, according to the Intergovernmental Panel on Climate Change (IPCC), agriculture accounted for 13.5% and forestry for 17.4% of total global anthropogenic GHG emissions; 50% of methane (CH₄); and 85% of nitrous oxide (N₂O) (US EPA, 2005).³

3. Agriculture and forestry practices that can help reduce and avoid atmospheric build-up of GHG emissions include afforestation (tree planting), forest management (silviculture, harvest and forest preservation), agricultural soil carbon sequestration (primarily through changes in cropland management and tillage), reduction in fossil fuel inputs through crop management decisions, and agricultural CH₄ and N₂O emission reductions through modifications to livestock and nutrient management. Generally, these options can be categorised as:

- Avoiding CO₂ emissions by preserving existing pools or sinks of carbon in tree biomass and soils (e.g. forest preservation, maintaining native grasses);
- Enhancing removal of atmospheric CO₂ (sinks) through sequestration (e.g. afforestation, planting perennial grasses);

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• Reducing fossil fuel-related CO$_2$, CH$_4$, and N$_2$O emissions (e.g. reducing tillage operations, substituting biofuel for fossil fuel, improving nutrient management).

Each of these options has advantages and disadvantages. Some options may be more susceptible to natural and anthropogenic disturbances, such as tillage and fire, others more potential for saturation of carbon sequestration over time, and others more potential for reversing and abandoning carbon sequestration practices. Additionally, agriculture and forestry can produce renewable feedstock for bioenergy production. Bioenergy feedstock and fuel production use fossil fuel, but it is generally thought that substituting bioenergy leads to a reduction in GHG emissions relative to fossil fuel (Farrell, 2006), although significant controversy surrounds the estimation of the actual GHG reduction when bioenergy expansion involves indirect land use changes (Searchinger, 2008).

4. Measuring GHG emissions is an important challenge in agriculture. Measurement is especially difficult given the spatial distribution of agricultural production over different climatic environments. Relative to industrial production, where potential and actual emissions can be measured at the point of release, or transportation emissions, which can be tied to fleet fossil fuel consumption, agriculture emissions are widely dispersed and tied to the nature of the soil, climate, and land and livestock management practices. A related accounting issue is inclusion and measurement of GHG impacts of global indirect land use change induced by a country’s or region’s biofuel incentives policies. If biofuel production incentives increase a country’s market price for a commodity that is used as a biofuel feedstock, domestic cropland may be used more intensively, crops may be reallocated on existing cropland, or the cropland base may be expanded onto non-cropland acres, leading to higher world market prices. Higher world market prices will induce both intensity and expansion of crop production and cropland use in other countries, releasing additional GHG emissions into the atmosphere. The potential indirect land use effect of biofuel feedstock production has led to the argument that GHG emissions from global land use change should be counted against the own country’s carbon accounting life cycle analysis (LCA) for biofuels, e.g. GHG analysis of maize ethanol produced in the US or rapeseed biodiesel produced in the EU should include not only US or EU land use change but other country indirect land use change (Fargione et al., 2008; Searchinger et al., 2008).

5. This paper addresses GHG emissions and environmental accounting in agriculture, particularly as applied to biofuel and associated land use changes. First, the LCA process used in environmental accounting models is developed and discussed. Second, issues and limitations of applying LCA to GHG emissions accounting in agriculture are identified. Third, because increasing biofuel production may induce indirect land use change (ILUC) and increase global GHG emissions from agriculture, the rationale for and efforts to link LCA models to LUC estimates are evaluated, especially with respect to estimation and reliability of ILUC and global GHG emissions. Finally, a brief summary of GHG accounting for biofuel highlights key issues and challenges identified in the paper. Annex A includes an inventory of alternative LCA models in common use.

2. Framework for GHG accounting – Life Cycle Analysis models

6. The most common framework employed in environmental and GHG accounting is LCA. LCA is a process analysis approach or model designed to evaluate all stages of a production and consumption system (i.e. from raw material extraction to ultimate product disposal) and is commonly used to address the environmental consequences (environmental footprint) of a product such as greater emission of criteria or toxic pollutants and their associated health impacts. Likewise, the atmospheric consequences (e.g. CO$_2$, nitrous oxide, methane) of fossil fuel use are associated with greater GHG emissions and increased global climate change. A LCA can also be used in other contexts, e.g. in nutrient mass balance or protein accounting in livestock, but most commonly in assessing the environmental performance of products. The basic steps in conducting an LCA include:
• Compiling an inventory of relevant energy and material inputs, outputs, and environmental releases;
• Evaluating the potential environmental impacts associated with identified inputs, outputs, and releases; and
• Interpreting the results and informing the public of potential energy and environmental implications of policy intervention decisions.

7. For example, LCA of fossil fuel consumption traces the fossil fuel from extraction through vehicle fuel consumption, it is frequently referred to as “well-to-wheels” accounting. Given that the pathways change when applied to a biomass energy system, it may be referred to as “field to wheels” accounting even though all energy and non-energy inputs are included in the LCA. Figure 1 illustrates potential pathways followed in tracing inputs, outputs, and net GHG emissions through a more general LCA framework.

8. The same general LCA framework is used to assess agriculture’s role in mitigating GHG (and other environmental pollutants. Ecosystem processes act to reduce GHG increases in the atmosphere by taking up and storing CO₂ in plants, trees, and soil as well as oceans, and frequently referred to as “carbon sinks.” In terms of GHG emissions, it is important to both reduce carbon emissions and to enhance carbon sinks or the absorptive capacity of plants, trees, soils, and oceans. There are a number of important ways that agriculture can enhance the capture and storage through terrestrial ecosystems. The coming of modern agriculture, especially since the 1950’s, has altered the agricultural and forestry GHG fluxes. As productivity increases, crop management improves, tillage intensity decreases, and soil conservation practices increase, the organic soil carbon stocks are being rebuilt (Paustian et al., 2006). At the same time, growing application of commercial fertilizers, especially nitrogen, has resulted in growing nitrous oxide emissions to the atmosphere (i.e. 300 times more potent GHG than carbon dioxide) and nitrogen leaching and phosphorus runoff into streams, rivers, and lakes contributing to problems like eutrophication and hypoxia.

9. Trends and technologies in modern agriculture, especially in many developed countries, have supported sustained yield growth in recent decades coupled with adoption of reduced tillage and improved nutrient use efficiency and management have contributed to improved carbon sinks (reduced GHG emissions), reduced nitrous oxide emissions, and freed up cropland to produce biomass crops.

10. At the same time, we have growing global consumption of meat and animal products, increased livestock numbers, and an increase in another GHG, methane released into the atmosphere, especially from large confined animal feed operations. Although management practices can reduce livestock emissions, opportunities for reduction may be long run in nature (breeding, genetic modification, nutrition) than in the plant and forestry management. In the US, livestock numbers during the last two decades have been decreasing for cattle and sheep, but increasing for hogs and poultry with livestock methane emissions fairly stable (Paustian et al., 2006).

11. Paustian et al. (2006) and others offer several solutions for managing agriculture and forestry to improve carbon sequestration in soils, reduce GHG emissions, and enhance carbon sinks, including:

• Efficient use of animal and organic manures, green and nitrogen fertilizers;
• Reductions of fallow or idle periods between crops;
• Adoption of agroforestry and production of high residue crops and grasses;
• Use of low- or no-tillage practices to maintain soil carbon stored;
• Protect carbon-rich soils (peat, forest, pasture land) and convert degraded crop land to grass or forest land, and restore degraded grass and forest land;
• Reduce nitrous oxide (and methane from flooded soils) emissions with efficient application, timing, and use of nitrogen-fixing crops, fertilizer, and animal manure;
• Reducing livestock methane and nitrous oxide emissions through improved manure handling and capturing and burning methane from digesters; and
• Reducing livestock methane from enteric fermentation by improved digestive efficiency, feed composition and quality, and animal breeding and genetic modification;

Each of these solutions may make an important contribution to reducing GHG emissions and storing carbon in the soil from agriculture and forestry. More importantly, if done in combination with other GHG mitigation practices, agriculture can have a significant impact on overall GHG emissions reduction. For example, more significant GHG reductions and competitive corn stover feedstock costs may occur in no-till maize production than conventional tillage (Miranowski et al., 2010).

Figure 1. Possible life cycle stages considered for LCA


12. Standard practice in many GHG accounting models is to first use a fuel cycle analysis (FCA) to identify all the fossil fuel inputs, outputs, and net energy value for the cycle. The LCA framework uses the FCA as input to derive CO₂e coefficients for each step of the process. FCA models derive net energy value or net energy benefit (equal to total energy output minus total energy input), or a close equivalent measure, net energy ratio (equal to energy output divided by energy input). Although there are discussions in the

4. Recently, studies by Baker et al. (2007) and Luo et al. (2009) indicate that with soil sampling over a deeper soil profile, no significant difference can be found between conventional, conservation, and no tillage in soil carbon sequestration.
literature about the most appropriate measure of net energy (e.g. Liska and Cassman, 2008; Farrell et al., 2006), these measures should be equivalent representations if careful and comprehensive accounting includes accurate measurement of all energy inputs entering the field and outputs exiting the system as fuel consumption.

13. Even though most LCAs use GHG emission coefficients established through previous research, serious challenges have been raised as to the validity of specific coefficient assumptions. Validation of GHG coefficients used in an LCA model is complicated, but important to the calculation of net GHG emissions from agriculture, and therefore important for an accurate and complete LCA. According to Jonas et al. (1999), the two methods of measuring or estimating net carbon fluxes into/out of a carbon reservoir are:

- The direct or flux-based method, where the flows of carbon into and out of a carbon reservoir are estimated directly and separately;
- The indirect or stock-based method, where the change in a reservoir’s carbon content is estimated during a specified time interval.

Under ideal conditions of exact and scale-adapted measurements, these two approaches should be redundant and give the same answer. Under real world conditions when measurement is less reliable, however, the results may differ. Since GHG emissions from agriculture are highly variable in space, time, soil, climate, management practices, and topography, different measuring methods may not produce similar GHG emissions estimates. To achieve statistically valid estimates requires collecting extensive and intensive research data, incorporating data into spatial process, or LCA models, and empirically verifying process models to establishing statistically reliable GHG emissions coefficients for spatial LCA models. Although costly, accurate measurement is important in determining GHG reductions from changing cropping patterns and management practices, estimating GHG increases from indirect land use, and implementing GHG policy initiatives (e.g. low carbon fuel standards, incentives and disincentives to reduce GHG emissions in agriculture). These circumstances lead to a variety of problems in measurement, monitoring, and verification, including establishing verifiable coefficients over space for GHG accounting and policy analyses (see, for example, Gallagher, 2009; Breidenich and Bodansky, 2009; Pattey et al., 2004).

14. Thus, the challenge of LCA in agriculture may not be tracing the pathway of energy and carbon inputs into the model and energy and GHG outputs out of the model, but rather, identifying the three following critical data components and coefficients to use in the analysis:

- Establishing country – and region-specific LCA coefficients for global comparisons of GHG impacts;
- Measuring and accounting for GHG impacts from global LUC as a result of country-specific agriculture policy initiatives; and
- Deriving GHG coefficients for the LCA appropriate to indirect LUC effects.

These challenges from an economic, environmental, and policy perspective, are addressed in part by Rajagopal and Zilberman (2007), and Zilberman et al. (2010).

5. Full GHG accounting can most easily be achieved experimentally and verified independently for small-scale experimental plots in the field. At greater scales, a number of flux and stock-based methods exist and may need to be combined in order to estimate full GHG accounts.
3. Limitations of Life Cycle Analysis for environmental accounting

15. LCA models are fixed coefficient, engineering or process models. These models are designed to provide a comprehensive accounting for all energy inputs, outputs, and GHG emissions in a production system. The results of a biofuel LCA are sensitive to the assumptions that the analyst used in the LCA model.6

- Assumptions and coefficient values;
- Baseline prices and factor input assumptions;
- GHG attribution decisions of the analyst, especially to co-products;
- Spatial dimensions and spatial boundaries established by the investigator;
- Inclusion of land use impacts; and
- Yield increase assumptions used in LCA.

Given the variables and assumptions noted above, direct comparison of the results from different LCA models is difficult. User friendly, public domain LCA models allow the user to change default values to better reflect existing conditions and environments, consider changes over time, and conduct simple sensitivity analysis. Frequently, LCA calculations of GHG emissions use average values reflective of country- and industry-wide averages. Although these estimates may be reflective of the country as a whole, they may overestimate GHG impacts of modern biorefinery technology employed in industry expansion (Liska and Cassman, 2008). Similarly, if industry expansion impacts world market prices and land use in other countries, then not including indirect LUC may underestimate GHG emissions. Thus, the results of LCA tend to be highly sensitive to the wide range of assumptions used to model and estimate net GHG changes. The sensitivity of the LCA results can best be illustrated by the Farrell et al. (2006) study that simply compared the net energy benefit and GHG emission estimates for previous studies. The comparison found a wide range of results that depended heavily on the input parameter assumptions. Studies considering the net energy balance of biofuel products and assessing GHG reductions of substituting biofuel for fossil fuel have produced very different results. Bureau et al. (2010) have used meta-analysis to analyse a large sample of these studies to isolate the major determinants of net energy value differences. They conclude that much of the variability is due to how inputs, such as nitrogen and labour, are controlled for and how fossil energy consumption is allocated to co-products. Because the LCA is a fixed-coefficient, process or engineering model as opposed to an economic model, energy consumption, production, and GHG emissions are calculated for a given set of inputs, outputs, and initial prices. Process models ignore substitution opportunities between inputs, outputs, and inputs-outputs in response to price changes. In other words, as prices change substitution occurs, especially over the long run. The input and output combinations used in production, as well as technologies, change over time in response to price changes in a dynamic agricultural environment. Because LCA models are insensitive to agriculture market prices, they may fail to capture the true behaviour of feedstock producers and processors (as well as everyone else in the system) in substituting less expensive inputs for more expensive inputs and adjusting input use in response to technological and output price changes. Therefore, the inflexible nature of the process model framework reduces the reliability of GHG emissions estimates from the LCA, especially in a dynamic production environment (Rajagopal and Zilberman, 2007). This is not to argue that LCA is not useful, but rather, that if input and output coefficients are not current, especially in an era of significant price shocks.

6. Cherubini et al. (2009) provide ranges of coefficients for various LCA components and explain why wide variation in assumptions may arise and impact the net change in GHG emissions. Larson (2006) also provides a review of LCA studies of liquid biofuel in the transport sector.
(e.g. shocks in energy prices), the LCA estimates may be misleading and thus need to be treated with caution.

16. Public controversy has recently surrounded the issue of GHG attribution in LCA analyses, especially when results are used for policy purposes. First, there are a number of GHG attribution decisions that have to be made by the analyst in multi-output conversion processes. A simple biofuel example is helpful in illustrating this point. Consider maize produced to make ethanol. A by-product of maize grain production is maize stover, which has the potential to be converted into cellulosic ethanol, used as animal feed or bedding, or directly returned to the soil as nutrients, organic matter, and erosion protection. Likewise, a co-product of maize ethanol production is distillers’ dried grains (DDGs) which account for about 1/3 of the original weight of maize grain fermented for ethanol but has different nutritional value. How should the LCA analyst attribute GHG emissions between the three products - maize ethanol, maize stover, and DDGs? Farrell et al. (2006) evaluated the sensitivity of the energy use allocation and GHG emissions between ethanol production and co-product production. The authors found that reallocation of emissions to co-product production had a significant effect on the net energy balance and GHG emission measures for biofuel. In summary, several studies were used in a meta-analysis by Bureau et al. (2010), and they concluded that the variability of net energy value (and thus GHG emissions) was related to how inputs were controlled for and how fossil energy was allocated to co-product consumption.

17. The scope or boundaries of the life-cycle analysis are also important when estimating GHG emission impacts. Smaller regions, like states, have more opportunities for carbon leakage or carbon export than larger regions, such as nations. The European Commission (2000) did sensitivity analyses on different LCA system boundaries and found that it had a significant impact on environmental performance not only for GHG but most other environmental factors as well. Particularly Figure 4-2 (p. 50) illustrates the influence of different boundaries on the on the results for rapeseed methyl ester relative to fossil diesel fuel for GHG, fuel use, and other environmental pollutants. Feng et al. (2010) compared what happens to GHG accounting when imposing a state-wide boundary versus a nation-wide boundary. To illustrate, a low carbon fuel standard (LCFS) established by a state (or province) may lead to carbon leakage from that state (or province) to other states (or provinces) as well as the nation and the globe. Imposing a LCFS in California may reduce the state’s GHG emissions, but may increase GHG emissions in other states, US, and globally. Similarly, importing non-fuel, high carbon-content products to the state, may reduce net carbon emissions in the state (or province) but not in the exporting state, country, or globally. An alternative analytical method to LCA is system-wide accounting (SWA), which considers the secondary effects of alternative fuels, such as the impact on global warming that may be caused by land use changes, food, fuel, and materials market adjustments, and demand for natural resources (Feng et al., 2010). In a SWA model, the degree to which maize ethanol reduces GHG emissions depends on how maize is produced, how maize is processed into ethanol, and what emissions would occur in the absence of maize ethanol. LCA takes into account the first two factors but not the third. The degree to which LCA estimated emissions differ from SWA estimated emissions depends on a number of factors, but especially the definition of the system boundaries. The more delimiting the boundaries of the LCA, the smaller the potential GHG impacts or it tends to reduce the GHG contribution.

18. The sustainability of biofuels has recently been questioned by Doornbosch and Steenblik (2007), Searchinger et al. (2008), and Farigone et al. (2008), especially with respect to the impact of biofuel expansion on global indirect LUC that increases GHG emissions. Typically, direct LUCs are presumed captured in the LCA process with full accounting of all GHG impacts related to biofuel production, distribution, and consumption. The carbon debt from other (indirect) LUC effects is not directly captured in the LCA process, especially in the case of global rainforest conversion to crop or pastureland. Unfortunately, LCA models were not designed to account for the GHG impacts of indirect LUC. If the authors are correct in their argument that these indirect LUCs should be included in the LCA GHG estimates and these changes are significant, many of the potential GHG reduction benefits of biofuel may
be offset by indirect LUC. Most studies that have attempted to estimate GHG emission impacts from global LUC first use agricultural models to estimate domestic and global LUC and then using the indirect LUC estimates, adjust the GHG reduction benefits derived from the LCA model. Section 4 addresses the appropriateness considering externality impacts of indirect LUC in an LCA to adjust GHG emissions from biofuel; discusses alternative domestic and global agricultural models designed to measure direct and indirect LUC; raises concerns about how LUC estimates derived from domestic and global agricultural models are used to adjust GHG emissions estimates derived from LCAs.

19. An important driver of LUC in agricultural models, both domestic and global, is future crop yield increase assumptions. The projected crop yield increases, in turn, determine future demands for cropland to meet food, feed, fiber, and fuel needs. Essentially, future yield increase assumptions together with future food, feed, fiber, and fuel needs determine cropland demand and drive LUC. Most agricultural models use historic linear yield trends to project future yield increases. Some preliminary US evidence indicates that corn yield increase may not only encounter structural breaks in the yield time series but may have an increasing trend, and more appropriately be estimated with a nonlinear specification or as the rate of yield increase over time (see, for example, Miranowski et al., 2010).

**LCA Application to Biofuel**

20. The LCA pathways for specific biofuels depend on the complexity built into the biofuel production system. To illustrate, a maize ethanol plant using the relatively simple dry-mill process begins with conventional maize production and management practices, converts maize to ethanol and other co-products, and follows the biofuel output through consumption. Initially, the maize ethanol industry was small and there were few significant environmental impacts, including LUC, discharges to soil and water, and reductions in net CO₂ emissions. Figure 2 depicts the basic biofuel pathways in estimating GHG emission impacts. As the maize ethanol industry expanded, so did the complexity of the biofuel production system. Direct and indirect LUC impacts became an issue, larger waste streams were accompanied by larger discharges of total water and waste, occasional cattle operations integrated to utilize co-products and produce biogas, and some new co-products were added. The process complexity evolved as technology improved, plants realized scale economies, and the process became more efficient, reducing GHG emissions per unit biofuel produced (Liska and Cassman, 2008), and recycling to the extent feasible became the norm.

21. To breakdown and illustrate the coefficient assumptions used in the typical maize ethanol case, Tables 1 and 2 provide a representative indication of GHG emissions from each step of maize ethanol from grain production through automobile consumption as derived by Farrell et al. (2006).
Table 1. Estimates of GHG emissions from the biomass production phase

<table>
<thead>
<tr>
<th>kg CO$_2$ e per hectare</th>
<th>Maize ethanol</th>
<th>Cellulosic (Switchgrass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertilizer</td>
<td>1 638</td>
<td>547</td>
</tr>
<tr>
<td>Chemicals</td>
<td>474</td>
<td>16</td>
</tr>
<tr>
<td>Transport</td>
<td>39</td>
<td>3</td>
</tr>
<tr>
<td>Fuel</td>
<td>362</td>
<td>341</td>
</tr>
<tr>
<td>Natural gas and LPG</td>
<td>107</td>
<td>0</td>
</tr>
<tr>
<td>Electricity</td>
<td>56</td>
<td>42</td>
</tr>
<tr>
<td>Irrigation</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Machinery</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>Total</td>
<td>2 703 kg CO$_2$e/ha</td>
<td>971 kg CO$_2$e/ha</td>
</tr>
<tr>
<td>Per litre</td>
<td>1 353 g CO$_2$e/L</td>
<td>124 g CO$_2$e/L</td>
</tr>
</tbody>
</table>

Source: Farrell et al. (2006).
Table 2. Estimates of GHG emissions from the biorefinery phase

<table>
<thead>
<tr>
<th>g CO₂e per L</th>
<th>Maize ethanol</th>
<th>Cellulosic (Switchgrass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport feedstock</td>
<td>49</td>
<td>51</td>
</tr>
<tr>
<td>Diesel</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Coal</td>
<td>885</td>
<td></td>
</tr>
<tr>
<td>Natural gas</td>
<td>365</td>
<td></td>
</tr>
<tr>
<td>Capital</td>
<td>8.8</td>
<td>29</td>
</tr>
<tr>
<td>Water</td>
<td>25</td>
<td>19</td>
</tr>
<tr>
<td>Effluent restoration</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Total biorefinery phase</td>
<td>1353 g CO₂e/L</td>
<td>124 g CO₂e/L</td>
</tr>
<tr>
<td>Total Ag Phase</td>
<td>780 g CO₂e/L</td>
<td>189 g CO₂e/L</td>
</tr>
<tr>
<td>Co-product Credit</td>
<td>-525</td>
<td>-106</td>
</tr>
<tr>
<td>Net GHG emissions</td>
<td>1608 g CO₂e/L</td>
<td>207 g CO₂e/L</td>
</tr>
<tr>
<td>Percentage difference</td>
<td>-18%</td>
<td>-88%</td>
</tr>
<tr>
<td>between ethanol and</td>
<td></td>
<td></td>
</tr>
<tr>
<td>conventional gasoline</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Farrell et al. (2006).

22. A frequent criticism of biofuel is more energy is used during biofuel production than contained in the final product. Farrell et al. (2006) compare several maize ethanol studies and countered this criticism. They find that a positive balance exists once co-product production (or GHG allocation to the co-product) is accounted for in the net energy benefit or balance (NEB) for maize ethanol. Biomass ethanol has an even better NEB. Miranowski and Rosburg (2010) illustrate that the initial steps of biomass acquisition are energy-intensive (i.e., harvesting, transporting, handling, and storage), Hill et al. (2006) found maize-based ethanol, soybean biodiesel and cellulosic ethanol all have NEB greater than one (energy output/energy input > 1), i.e., more energy output than energy input. Maize-based ethanol has a NEB of 1.25, or 25% more biofuel energy content than fossil fuel energy input. Soybean biodiesel has a NEB of 1.93 (similar to rapeseed biodiesel) for the production process, and increases to 3.67 when by-product production is removed. Cellulosic ethanol has a potential NEB greater than 4.0 (Hill et al., 2006). Therefore, recent developments in cellulosic biofuel production have weakened concerns over biofuel net energy loss.

23. Underlying the energy input-output discussion is a Fuel Cycle Analysis (FCA), which is the basis for LCA modelling and estimating GHG emissions. For example, we can compare the GHG emission reductions across ethanol feedstock. The results from LCAs for alternative ethanol feedstocks are reported in Tables 3 and 4. The GHG and net carbon emission reductions vary significantly by biofuel feedstock.
Table 3. Estimated GHG emission reductions from biofuels

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>GHG emissions reductions (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize-based ethanol</td>
<td>12 (Hill et al.)</td>
</tr>
<tr>
<td></td>
<td>13 (Ferrell et al.)</td>
</tr>
<tr>
<td></td>
<td>20 (Kopp)</td>
</tr>
<tr>
<td></td>
<td>18-29 (Wang)</td>
</tr>
<tr>
<td>Sugarcane ethanol</td>
<td>65-105 (Carriquiry et al.)</td>
</tr>
<tr>
<td>Sugarbeet ethanol</td>
<td>30-60 (Carriquiry et al.)</td>
</tr>
<tr>
<td>Soybean biodiesel</td>
<td>41 (Hill et al.)</td>
</tr>
<tr>
<td>Rapeseed biodiesel</td>
<td>20-80 (Carriquiry et al.)</td>
</tr>
<tr>
<td>Mix vegetable oil Biodiesel</td>
<td>55-81 (de la Rua et al.)</td>
</tr>
<tr>
<td>Palm oil biodiesel</td>
<td>30-75 (Carriquiry et al.)</td>
</tr>
<tr>
<td>Cellulosic ethanol</td>
<td>89 (Kopp)</td>
</tr>
<tr>
<td></td>
<td>85 (Wang)</td>
</tr>
<tr>
<td></td>
<td>88 (Service)</td>
</tr>
</tbody>
</table>

24. Other types of offsets, such as those that reduce methane emissions and nitrogen oxide emissions are also valuable, but they do not have a strong influence on the competitive balance between cropland, pasture, and forestland. Maize ethanol has the least impact on reducing GHG emissions, with an estimated 12–29% decrease (Hill et al., 2006; Ferrell et al., 2006; Kopp, 2006; Wang, 2005). Soybean biodiesel is estimated to reduce GHG emissions 41% (Hill et al., 2006). Cellulosic feedstock has the most promise for reducing GHG emissions in ethanol production. Predictions range from 80-88% (Kopp, 2006; Wang, 2005; Service, 2007). Although we have a significant GHG reduction range for the other feedstock in Table 3, the midpoint values indicate significant GHG reduction. However, other environmental performance indicators may point in the opposite direction, including ILUC, acidification, and eutrophication impacts relative to fossil fuels.

25. In addition to biofuel policy, climate change policy could also influence land use if forestry and agricultural offsets are included in the policy. Carbon offsets, or percentage reductions in net carbon emissions associated with different feedstocks, are credits for carbon sequestration that occurs on agricultural or forestland by changing land management practices. Offsets can be generated by a host of activities, including conversion of agricultural land to forests (afforestation), extending timber rotations, improving forest management, shifting from conventional tillage to no-tillage, reducing methane emissions from livestock operations, and reducing nitrogen oxide emissions from production agriculture. The amount of carbon offset by feedstock differs with the type of crop and how the crop is managed. Table 4 provides estimates of net carbon reductions from managing for different feedstock on the landscape.
Table 4. Net carbon emission reduction (%) offset (carbon emissions reduction) rates – life cycle analysis

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Ethanol</th>
<th>Electricity</th>
<th>Biodiesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>43</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Soybeans</td>
<td></td>
<td></td>
<td>96</td>
</tr>
<tr>
<td>Sorghum</td>
<td>45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barley</td>
<td>43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oats</td>
<td>39</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soft White wheat</td>
<td>42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hard Red Winter wheat</td>
<td>41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Durum wheat</td>
<td>39</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hard Red Spring wheat</td>
<td>42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sugar</td>
<td>28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Switchgrass</td>
<td>81</td>
<td>87</td>
<td></td>
</tr>
<tr>
<td>Hybrid Poplar</td>
<td>72</td>
<td>89</td>
<td></td>
</tr>
<tr>
<td>Willow</td>
<td>74</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>Softwood log residue</td>
<td>68</td>
<td>91</td>
<td></td>
</tr>
<tr>
<td>Hardwood log residue</td>
<td>69</td>
<td>91</td>
<td></td>
</tr>
<tr>
<td>Bagasse</td>
<td>86</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>Maize residue</td>
<td>84</td>
<td>91</td>
<td></td>
</tr>
<tr>
<td>Wheat residue</td>
<td>79</td>
<td>88</td>
<td></td>
</tr>
<tr>
<td>Sorghum residue</td>
<td>73</td>
<td>76</td>
<td></td>
</tr>
<tr>
<td>Barley residue</td>
<td>56</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>Rice residue</td>
<td>55</td>
<td>62</td>
<td></td>
</tr>
<tr>
<td>Softwood mill residue</td>
<td>76</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>Hardwood mill residue</td>
<td>76</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>Manure</td>
<td></td>
<td></td>
<td>91</td>
</tr>
</tbody>
</table>


Achieving sustainability in bioenergy production systems

26. As reported in several studies discussed in the previous section, maintaining sustainability of biofuel systems is a complex issue because it can have major impacts on several dimensions of the agricultural production and ecological system, ranging from water consumption and quality, to landscape and erosion, to new pathways of production, to underlying market issues, and social choices. Sustainability analysis reaches beyond the narrow definition of a fuel cycle based LCA (e.g. Hill et al., 2009), and fits the broader definition pursued by national environmental agencies and non-government organisations. This approach to LCA is more holistic in nature and addresses the fate of outputs and residuals into various environmental media. Figure 3 identifies the components that must be considered in maintaining
sustainability of bioenergy production systems as well as the pathways that are followed from biomass feedstock production to biofuel production through biofuel consumption.

Figure 3. Critical components of sustainable bioenergy production

Source: Smith et al., presentation (2005).

27. Biofuel LCAs or “field-to-wheels” GHG and other residuals accounting exercises differ in important ways from the more traditional “well-to-wheels” analysis. Extraction, transport, and conversion of fossil fuels into liquid transportation fuels are significantly different from production, transport, and storage of biomass feedstock and ultimately conversion into liquid biofuel. Note in Figure 3 that much of the biogenic CO\textsubscript{2} is recaptured by the following biomass feedstock crop, reducing net CO\textsubscript{2} emissions. Although not directly captured by the LCA model for biofuel, sustainable production of biomass feedstock is an important dimension to be considered, particularly in terms of soil, air, and water quality. Some studies, such as ALTF (2009), attempt to insure sustainability of maize stover production by constraining corn stover harvest to cropland with maize grain yields exceeding 150 bushels per acre (or 9.35 MTha\textsuperscript{1}).

28. There are a number of approaches to bringing sustainability into a LCA of biofuel. In the European Commission’s (2000) framework of the FAIR V Programme, sustainability was addressed through a comprehensive LCA of environmental performance that not only considered GHG emissions but other environmental factors (i.e., air, water, land, and human) affecting the landscape. Specific factors included in the analysis were use of fossil fuel, GHG effect, acidification, eutrophication, summer smog, nitrous oxide, human toxicity, and biodiversity and soil quality. The analyses and comparisons were done for several biomass feedstock and production systems making comparisons between biofuels within each country and between biofuels in different countries. In this way they could identify the most favorable biofuels in each country and the EU, respectively, and aid in LCA as well as socioeconomic and political analyses. Assigning weights or values to the various environmental indicators was left to the value judgment of the reader, but the advantages and disadvantages of of biofuel relative to fossil fuel were clearly enumerated. Other studies take a more integrated approach, e.g. Malcolm et al. (2009), attempt to incorporate other environmental residuals from expanded biofuel production into a mathematical programming model.
Integrating LCA and economic sustainability into biomass feedstock analysis

29. In this section, we consider the economic sustainability of biomass ethanol production in terms of the implicit price of carbon needed to sustain biofuel production. In response to the growing global interest in sustainable energy, reflected in recent legislative incentives and directives mandating biofuel use, a cellulosic ethanol model was developed by Miranowski and Rosburg (2010) to assess the economic sustainability of different biomass fuel systems and the cost of achieving GHG reductions with alternative biomass feedstock. Miranowski and Rosburg (2010) use a breakeven model for cellulosic feedstock and biofuel processing systems with LCA coefficients embedded to estimate potential GHG reductions for each feedstock and the carbon price necessary to sustain cellulosic ethanol markets. The model calculates the biomass suppliers’ minimum willingness to accept (WTA) per ton of feedstock and the processors’ maximum willingness to pay (WTP) for the marginal ton of feedstock delivered for alternative production environments (e.g. feedstock, yields, input requirements, land opportunity costs, alternative collection, storage and transportation systems, and policy scenarios). Seven feedstocks are evaluated: maize stover, switchgrass, miscanthus, wheat straw, prairie grass, farmed trees, and forest residue. Under market equilibrium conditions, as well as most policy and oil price scenarios, cellulosic feedstocks are not economically viable. Using LCA parameters based on GREET 1.8c, Miranowski and Rosburg then calculate the GHG emissions savings from cellulosic ethanol on a per ton feedstock. Based on the model estimates, farmed trees, maize stover, and forest residue provide the greatest GHG savings per ton of feedstock.

30. In the final step of their analysis, they use the gap between the minimum WTA and maximum WTP, combined with the GHG savings per ton of cellulosic feedstock to derive the carbon price necessary to sustain a cellulosic ethanol market for each feedstock. These estimates are reported in Figure 4. At a USD 75 per barrel oil price, a carbon price of USD 65 to USD 160 per ton CO₂e is needed to sustain a cellulosic ethanol market. Even at a USD 90 per barrel oil price, the carbon price needed to sustain a cellulosic ethanol market is between USD 40 and USD 125 per ton of CO₂e.

Applications of comprehensive life cycle analyses to alternative feedstock in humid and tropical regions

31. There are several recently published LCA studies on tropical and temperate crops that focus on specific feedstocks and countries or regions. These studies do not attempt to estimate the global indirect LUC impacts, which with a few exceptions, would be small or non-existent, but they perform a comprehensive LCA, including environmental performance characteristics that provide a more complete sense of the sustainability of these biofuels. Menichetti and Otto (2009), provide a useful survey and comparison of energy balance, GHG impacts, and related data on feedstocks that included sugarcane, sugar beets, rapeseed, palm oil, soy oil, sunflower oil, and cellulosic crops. Cherbini and Ulgiati (2010) provide LCAs for various crop residues as feedstock and emphasize the need for best management practices (including rotation, tillage, nutrient management suitable for soils and climate) and sustainable harvest rates to minimize soil carbon losses.

32. With respect to more tropical crops, Ometto et al. (2009) perform a life cycle assessment of fuel ethanol derived from sugarcane as 100% of the vehicle fuel in Brazil using study cases at sugarcane farms and fuel ethanol industries in the northeast of Sao Paulo State, Brazil. The analysis covers the following emission-related impact categories: global warming, ozone formation, acidification, nutrient enrichment, ecotoxicity, and human toxicity. The results demonstrate that sugarcane ethanol uses a high quantity and diversity of non-renewable resources over its life cycle. The high water consumption is due to the sugarcane washing process. Harvesting contributes most to global warming and photochemical ozone formation due to burning during harvest and the emissions from diesel fuel use.
Figure 4. Carbon price needed for cellulosic ethanol market existence

Source: Miranowski and Rosburg (2010).
Note: Values based on the assumption of no other policy incentives to either the ethanol processor or biomass supplier (i.e. no tax credits or subsidies).

33. Ometto and Roma (2010) evaluate sugarcane LCA emissions when fuel ethanol production is coupled with cogeneration of electricity in Brazil. They conclude that improved environmental quality and energy efficiency could be achieved by not burning following sugar cane harvest and by using the biofuel in tractors, trucks, and buses. Macado et al. (2008) use an LCA analysis of sugar in Brazil to demonstrate the importance of cane productivity and ethanol yield on energy balances and GHG emissions. The energy balance for palm oil derived methyl ester in Brazil and Columbia is calculated by Angarita et al. (2009). Unfortunately, they do not complete a full LCA but show positive energy balances for palm oil.

34. Luo et al. (2008) examine environmental and economic impacts of Brazilian ethanol industries (sugarcane based ethanol) using a comparative life cycle assessment framework. They compare current bioethanol production from sugarcane and electricity generation from bagasse and future bioethanol production from both sugarcane and bagasse and electricity generation from wastes. The fuel life cycles analysis includes gasoline production, agricultural production of sugarcane, ethanol production, sugar and electricity co-production, blending ethanol with gasoline to produce E10 and E85, and the use of gasoline, E10, E85, and pure ethanol. The LCA results indicate that ethanol fuels are better options than gasoline in terms of abiotic depletion, GHG emissions, ozone layer depletion, and photochemical oxidation; while gasoline is a better option in terms of human toxicity, ecotoxicity, acidification, and eutrophication.

35. Hu et al. (2004) examines the life cycle economics (lowest cost), environment impacts (low pollutants), and energy consumptions (higher efficiencies) of Chinese automobiles fuelled by bio-ethanol blends. A generic gasoline fuelled car is used as the baseline while a cassava-based E85 fuelled FFV as comparison. Hu et al. use the GREET-1.6 model and the vehicle Life Cycle Inventory. A cassava-based E85 fuelled FFV emits lower life cycle CO₂, CO, HC, and PM pollutants, higher NOₓ than a gasoline fuelled car does, and has a lower combined environment indicator than a gasoline car. The authors indicate that the cassava-based E85 fuelled FFV would become more viable as the price of cassava decreases or the price of gasoline increases, but that cassava ethanol was not competitive with conventional gasoline at existing prices.
36. Roy et al. (2007) perform a life cycle assessment of rice in Bangladesh to examine the environmental impacts of different rice production processes (i.e. the vessel, medium-boiler, and untreated processes are compared). Specifically, they look at energy consumption and CO₂ emission in the rice life cycle. The LCA results show a gradual decrease in energy consumption and CO₂ emission from the vessel process to untreated process (vessel > medium-boiler > untreated). They conclude that the most environmentally sustainable process is to mill but not process the rice further.

37. Nguyen and Gheewala (2008) perform a life cycle energy and environmental performance analysis of molasses-based ethanol as a 10% blend with gasoline as a transportation fuel in Thailand. They use GREET to derive emission factors and consider the following parameters: 1) energy use, specified as a) net energy use (total fossil and non-fossil energy use, excluding energy recovered from system co-products), b) fossil energy use, and c) petroleum use; 2) environmental impact potentials (global warming, acidification, nutrient enrichment, and photochemical ozone creation); and 3) land use (for growing feedstock/sugar cane to produce ethanol). They compare these alternatives based on the gasoline equivalent consumed by a new passenger car to travel a specific distance. Molasses is a by-product of the sugar industry and is a common feedstock for the alcohol industry in tropical countries. Taking advantage of available supply, a simple conversion process, and existing sugar-based distilleries, the Thai government encourages fuel ethanol production from molasses. Silalertruksa et al. (2009) used a consequential LCA to evaluate possible future changes in crop production systems and determine the induced LUC and GHG implications. Their analysis indicated that increased productivity of sugarcane and cassava yielded great GHG net benefits than did land use expansion.

38. Using a comprehensive LCA of the fossil fuel benefits and avoided GHG emissions of various options to meet the EU biofuels goals in Spain, Lechon et al. (2009) conclude that the GHG emission were sensitive to the source of cereal or oilseed feedstock used to produce biofuel, the biorefinery’s ability to co-produce electricity, and the mix of biofuel produced (i.e., emphasis on ethanol would maximize GHG benefits and biodiesel emphasis would maximize net fossil fuel savings). Bernard and Prieur (2007) use an LCA and biofuel market analysis to determine the impacts on implementing the EU biofuel goals using domestic feedstock to produce ethanol and biodiesel. They found that biofuel would only be competitive if crude oil prices remain high or if modulated tax exemption was adjusted accordingly. Then the 2010 5% reduction goal for GHG emissions in transportation would be met.

39. Another EU study by Reinhard and Zah (2009) used a consequential LCA to evaluate the direct and indirect environmental impacts of Switzerland replacing one % of their current diesel consumption with imported soybean diesel from Brazil or palm diesel from Malaysia. They conclude that considering global scale impacts of imported biofuel, this biofuel would have negative environmental consequences and no net GHG benefits. Similarly, Lapola et al. (2010) demonstrate that carbon losses from indirect LUC can exceed carbon savings from biofuel exported from Brazil to the EU. They also provided suggestions alternative practices that could be adopted in by Brazilian agriculture to improve net carbon saving for exported biofuel.

40. Two exploratory LCA studies of lignocellulose feedstock for biofuel production were recently reported. Singh et al. (2010) focus on key issues for properly quantifying GHG emissions in an LCA of lignocellulosic biofuels so as to produce accurate results using a review of past biofuel LCAs. Uihlen and Schebek (2009) consider possible biorefinery variants and conclude that the GHG impacts of biorefineries in some impact categories are an improvement over fossil fuel but not in others.

4. Estimating ILUC impacts on LCA with agricultural models

41. As a preface to the discussion, it is important to note that there are economic arguments for not including GHG emissions from indirect LUC in the biofuel LCA. The standard argument of applied
welfare economics does not support inclusion of indirect LUC in biofuel LCA models. In effect, inclusion of this externality is to treat biofuel energy differently than we treat other forms of energy. Alternatively, this can be viewed as a pecuniary externality, i.e., the consequence of markets operating to efficiently allocate resources, as opposed to incomplete markets or a market failure due to the production or consumption of an individual impacting others without their permission or compensation. In a recent National Research Council report (NRC, 2010) on monetizing the externalities from energy production and use that, the committee addressed this issue:

Our task in this report is to identify and monetize the externalities associated with energy production and consumption. The committee discussed whether these externalities should include both the direct land use effects and the indirect effects and have chosen to report only the direct land use effects (as captured in GREET). In doing so, we by no means dismiss the potential importance of indirect land use effects in policy design, but we do not wish to treat externalities associated with the production of biofuels any differently than the externalities associated with the production of other fuels. (p. 137)

Zilberman et al (2010) identify several reasons why regulators should avoid including indirect land use change in calculating LCA-based biofuel policies, such as a low carbon fuel standard or a renewable fuels standard. They argue that holding individuals responsible for activities controlled by others violates the principles of externality regulation, indirect land use change estimates are unstable, especially over time and over policy choices, that uncertainty may discourage investment in biofuel development, and global solutions are need as opposed to partial solutions given the nature of the problem (Zilberman et al., 2010). This is not to say that inclusion of global LUC impacts on GHG emissions from biofuel does not have support in the environmental, legal, and science communities (see e.g., Ravindranath et al., 2009; Hertel et al., 2010) but rather, that it is inconsistent with how we treat other nonmarket externalities associated with carbon fuels.

42. Given this caveat, we will now turn to a discussion of estimating LUC from agricultural models. Current agricultural models are not designed to measure changes in GHG emissions, but rather to estimate the economic or market impacts, including changes in land use (or in some cases implications of changing land values for land use), when policy shocks are introduced into the model. GHG releases from LUC (i.e. carbon debt) have been identified as a significant contributor to the environmental profile of biofuels. As previously stated, direct LUCs are presumed captured in the LCA process with full accounting of all the GHG impacts related to biofuel production, distribution, and use. The carbon debt from indirect LUC (or ILUC) effects, such as conversion of pastureland to cropland or forestland to pastureland, is not directly captured in the LCA process. In response, analysts have attempted to adjust GHG emission estimates from the LCA by inferring ILUC estimates based on cropland (and pasture and forestland in national agricultural models) LUC from agricultural models, or by shocking an agricultural model and feeding these impacts into a land use adjustment model. These land use adjustment estimates are calculated for a shock at a given point in time, and land use change is a more gradual process driven by a number of causal factors over time. In coupling LCA and agricultural models, analysts are joining incompatible tools. The LCA is developed using very specific coefficients for the valuation of products (or processes). Agricultural models use more general data of varying degree of detail for different regions and countries. At the global level, LUC data are typically estimated for cropland, occasionally for pastureland, and more rarely for forestland. Changes in other global land use (including global pasture and forestland) are typically inferred from projected changes in global cropland. Thus it is difficult to determine for which policy-related questions this approach is capable of providing reliable estimates or answers.

43. Agricultural management practices and cropping patterns are also key factors in estimating GHG emissions associated with LUC because these factors affect biogeochemical cycles, soil and water quality and availability, and emission and sequestration of GHGs. Sustainable crop management practices (no-till
and no-till with cover crops) can reduce the payback period, which is the time required for biofuels to overcome carbon debt due to LUC and provide cumulative GHG benefits (Kim et al., 2009). Alternatively, this can be viewed in terms of net carbon emissions reductions (Table 4) from feedstock choices and associated crop management practices.

44. The choice of agricultural models to estimate LUC effects depends on the boundaries imposed by the analyst on the LUC and LCA assessments. More specifically, if the analyst is only interested in domestic direct and indirect LUC and associated GHG emissions, then a country-level agricultural model should suffice. For example, in a country with a smaller agricultural sector, a biofuel shock may have a significant impact on LUC and country food prices but may have a limited impact on world food prices. In this situation, a country agricultural model of LUC and LCA should be sufficient to capture the necessary adjustment in GHG emission. If the policymaker or analyst is focusing on estimating global direct and indirect LUC and the effects on global GHG emissions, a global agricultural model that captures both domestic LUC (due to a biofuel policy shock) and global LUC (due to the policy shock impacting world market prices) would be required to achieve comprehensive accounting of GHG emission adjustments.

45. Agricultural models of LUC are based on two different modelling approaches: partial equilibrium (PE) and computable general equilibrium (CGE) models. PE models, such as the CARD/FAPRI model, typically focus on agricultural product markets and trade, treat agriculture as largely independent of the rest of the economy, and handle macro variables as exogenous to the model (e.g., price of oil). The main advantage of PE models is that they can handle more detail on agricultural products, markets, trade, production technologies, environment, land use, and policy shocks or interventions.

46. The CGE models, best represented by the GTAP group of models, operate quite differently from PE models. These models operate at a higher level of aggregation with little product detail, both in terms of products and industries considered. CGE models have the advantage of capturing linkages between agriculture and the rest of the economy, and capturing broader global trade implications (Hertel et al., 2010). Hertel et al. (2010) also argue that the economy-wide feedback loops better capture opportunity costs of mitigation strategies in a dynamic environment, input reallocation, and international production patterns. Unfortunately, most CGE models are not dynamic and do not capture adjustment lags over time, e.g., afforestation and deforestation are longer run processes not well captured in static analyses. Critics also argue that these models are too aggregate and do not capture many characteristic of the agricultural sector. This criticism holds with respect to LUC and the nature of land being converted which is important in estimating GHG impacts of indirect LUC. In defense of this approach, other statistical models or “side-analyses” are frequently used to capture the dynamic of adjustments (such as LUC within countries and regions) over time based on the aggregate results of the CGE models (e.g. Hertel and Sohngen, 2009).

47. There are also several country- and region-specific agricultural models capable of estimating country or region LUC, but these models are not capable of evaluating the indirect effects of a biofuel policy shock in one country or region on another country’s or region’s LUC. Good illustrations of this approach are contained in the recent issue of Biomass and Bioenergy (2010) that reports integrated analyses carried out on the EU’s REFUEL Project. The IIASA modelling framework was used to provide quantitative results for the land use dynamics from food, feed, and biofuel production, subject to constraints on food production, nature conservation, and ecological preservation, and how the results relate to increasing land productivity in Eastern Europe and second generation biofuel development. Studies using other modelling frameworks frequently produce different LUC impacts, especially when dealing with different assumptions about the interface between cropland and pastureland, and pastureland and forestland. A more detailed discussion of current agricultural models that address domestic and global land

7. A more detailed discussion and evaluation of recent CGE models can be found in Platanik and Roson (2009).
use is contained in Annex B. PE, GE, and integrative assessment models are discussed, as well as domestic versus global agricultural models. Models discussed in Annex B include both partial equilibrium models: CARD/FAPRI, FASOM, POLYSIS, IMPACT, GLOBIOM, IIASA, and general equilibrium models: GTAP and associated integrated assessment models that typically operate within a CGE framework.

**Linking agricultural models estimating ILUC with LCA models**

48. With the growing awareness of climate change issues and demand for “sustainable behavior,” the concept of indirect LUC has become a highly debated and controversial topic. According to Reijnders (2010), in California (the first state to confront ILUC), an intent of Californian lawmakers to include an ILUC factor in their biofuel policies has been opposed by the vested interests in transport biofuel production. In the US, the debate surrounding EPA’s implementation of the Renewable Fuels Mandate (RFS) (2007 Energy Independence and Security Act), ILUC was initially considered in rulemaking but not included specifically in the final rule. In the EU, the Council approved a policy proposal (2007) for 10% renewable energy in road transport fuels by 2020. The Renewable Fuels Directive (RED) defined sustainability criteria that renewable fuels must meet with respect to direct LUC, and under RED the EU Commission must report by the end of 2010 on ILUC and make proposal to address the issue where appropriate. Also, The Fuel Quality Directive (FQD) includes sustainability criteria for reductions in GHG emissions (6% by 2020) from fuel consumed in the EU. Some large EU countries such as Italy and Spain are firmly against inclusion of an ILUC factor in European biofuel policies, while the European Commission is apparently in favour of the inclusion. Another avenue supporting international biomass development for energy is the Global Bioenergy Partnership (GBEP). GBEP involves the governments of many EU and OECD countries, several developing countries, the UN agencies, and other international groups in stimulating research, development, and commercialisation of biomass production, delivery, and conversion to energy, particularly in developing countries. It serves as a forum for facilitating international cooperation and information exchange, fostering sustainable practices for production and efficient use of biomass, and supporting bioenergy policy-making and market development. In particular, GBEP is working to formulate a harmonized methodological framework to analyse the full well-to-wheels lifecycle of biomass and transport biofuel. If successful, this effort should contribute to harmonized treatment of the ILUC issue at least among participating countries.

49. We can probably best characterize the two schools of thought that have developed around global ILUC and the related GHG emission impacts as: “we know it is not zero, so some estimate is better than nothing” or “we should not be including ILUC in policy decisions, and additionally, we are attempting to measure the unmeasurable.” This characterization is not to minimize the detrimental impacts of ILUC on GHG emissions, but rather, to reflect on the rationale for including ILUC in policy decisions and our ability to obtain reliable estimates of ILUC from global agricultural or CGE models to use in adjusting LCA for biofuel policy decisions.

50. Generally, the approach used to link LUC estimates from agricultural models with LCA models is as follows. First, agricultural models with LUC components are shocked into producing X many additional gallons of ethanol (typically maize grain based) to estimate the associated LUC that would be induced by the shock (either maize price or quantity shock). Then, the acreage response to the shock is used to determine the additional acreage and where the expansion will occur. Assumptions are made by the analyst regarding what lands are being converted and what GHG emission (or carbon debt) coefficients are associated with converting that type of land. Depending on the assumptions made, forestland could be converted to pastureland or cropland, pastureland to cropland, or sequentially, forestland could be converted to grazing land and grazing land to cropland in a transitional process. The increased GHG emissions are then divided by increased ethanol production to derive the LCA indirect LUC coefficient referred to in Figure 2.
51. Among the first researchers to address indirect LUC was Searchinger et al. (2008), who argued that any potential GHG benefits from maize-based ethanol relative to conventional gasoline are more than offset by the GHG emission from indirect land use change. They used CARD/FAPRI model runs to determine LUC on cropland in Brazil. Then the cropland increase was attributed to converting rainforest and those carbon debt coefficients were applied to adjust the GHG impacts from the maize ethanol LCA. Further complicating their conclusions, Feng and Babcock (2008) argued that it is impossible to completely distinguish between direct and indirect land use change since ethanol feedstock was typically produced on both old and newly converted land. Not all converted land is used for biofuels as some land is used to produce animal feed. Therefore, to determine the direct and indirect LUCs from biofuel production would require a complete accounting of feedstock from field to refinery.

52. Second, the analyst could build GHG or carbon coefficients directly into the agricultural land use change model to capture both crop mix and land use effects by major producing region. Although there are efforts underway that employ this approach, they are not operational; additionally, this type of approach still requires analytical judgments about the types of new land that will be brought into production.

53. Two caveats need to be mentioned. First, we are combining an economic-based agricultural LUC model with a fixed coefficient LCA process model as discussed previously. The agricultural model has some degree of substitution among inputs and outputs as prices change, while the process model provides no such opportunities. When agricultural prices change, so should the GHG estimates for biofuel. Essentially, adjusting the LCA analysis with the LUC data is combining incompatible process and economic models. If the LUC component of the agricultural model has sufficient detail, building the carbon coefficient into the agricultural model may lead to more accurate estimates of GHG emissions from LUC.

54. It is important to note that if the goal of the LCA is to include global indirect LUC, only a global agriculture model is capable of measuring such changes. There are two models, CARD/FAPRI and some versions of GTAP, which address global agriculture and LUC. Although other models do capture global trade linkages, they are not designed to address global indirect LUC.

55. Because the global agricultural models capable of estimating LUC impacts differ in many respects, it is difficult to directly compare the LUC results and appreciate why the results differ. It is even more difficult to determine which set of LUC estimates represent more “reliable” input into adjusting GHG emission estimates from LCA models (e.g. maize grain to reflect indirect LUC consequences). One approach that has been used to illustrate the differences is to compare the LUC elasticities from a demand shock for ethanol through the derived demand for maize grain. Babcock (2009a) provided estimates of the “implied acreage response elasticities” to an additional billion gallons of maize ethanol production, comparing runs of GTAP and CARD/FAPRI models both for the US and global agriculture. Babcock concluded that GTAP predicts a US agricultural land use change of 250 000 acres and 700 000 acres in the rest of global agriculture in response to a one billion gallon increase in maize ethanol production. GTAP predicts a US agricultural land use change of 300 000 acres and global agriculture change of 400 000 acres per billion gallons of increased ethanol production. GTAP and CARD/FAPRI demonstrate similar US “implied acreage response elasticities” but CARD/FAPRI approaches almost double the indirect acreage response in global agriculture.

56. Why would these models provide varying projections of land use change when they are submitted to similar shocks? In his testimony before the US Congress, Babcock (2009a) indicated a number of possible reasons. He argues that we come pretty close on US agricultural land use allocation in response to biofuel policy shocks because we have been producing ethanol biofuel for almost 30 years. We are not able to derive solid LUC estimates outside the US because of modellers lack data and knowledge about what is happening in other countries. Further, we have little or no data on what types of lands are
being converted in response to these market price shocks in other countries. He concludes that the precision with which agricultural models can estimate such global LUC induced by the market is low. Thus, the range of uncertainty is high for any GHG emission estimates adjusted for global LUC.

57. In a recent “battle of the models” paper by Witzke et al. (2010), the authors employ a decomposition approach to assess the ILUC results from global modelling efforts including FAPRI (CARD-Iowa State), IMPACT (IFPRI), GLOGIOM (IIASA), AGLINK (OECD), DART (IfW), LEITAP (LEI), and GTAP (Purdue). This comparison goes back to a workshop organised jointly by OECD, the Joint Research Centre of the European Commission, and the European Environmental Agency of Denmark which was held in Paris in January 2009 (OECD-JRC-EEA, 2009). This paper uses the detailed modelling results to form comparable aggregates in terms of regions and products. Each model considers the land use change under three biofuel scenarios and the models assumptions with respect to yield increases versus land increases. Although this paper provides some interesting insights into model operation and projected land use changes, it does not answer the question of how we should measure indirect land use changes or if these measures of ILUC are appropriate for inclusion in LCA.

58. Adding a new dimension to the ILUC issue, Havlik et al (2010) use GLOBIOM to argue that second generation biofuel using woody biomass from sustainably managed existing forests would reduce the ILUC factor and GHG emissions by 27% by 2030 relative to the “no biofuel” alternative. Because GLOBIOM contains bottom-up agricultural and forestry management practices, sustainable forestry management improves forest productivity and reduces the need for dedicated forest plantations that would compete directly for agricultural land (Havlik et al., 2010). Improved technologies, biological characteristics, management, and information systems, raise the potential to improve crop and livestock yields and productivity, and reduce negative ILUC and GHG impacts, or potentially eliminating such impacts (see, for example, Sexton and Zilberman, 2010, and Zilberman et al., 2010).

5. Summary and implications

59. By definition, an LCA is a comprehensive accounting of all the energy inputs into the process and outputs out of the process, including GHG and other emissions. Ideally, sustainability should be incorporated into the system. Others have argued that increased GHG emissions in the biofuel system from global LUC should be included in the LCA for biofuel as well. Anyone who has studied market and trade analysis appreciates the fact that increased demand for biofuel feedstock and related market price shocks will increase returns to cropland and thus competition for agricultural land. These market price impacts will reverberate through global commodity markets and induce both domestic and global LUC. At the same time, three caveats need to be raised with respect to adjusting the LCA GHG emissions estimates for global LUC. First, in dealing with externalities (consequences not captured in market activities, generally the result of poorly defined property rights) from other energy forms of energy or carbon sources, we do not attribute global LUC effects to the fuel or adjust GHG emissions from an LAC. These effects are referred to as pecuniary externalities or market-induced effects. Second, the LCA is a process analysis that is unresponsive to price changes that frequently occur in the market system, while economic models are responsive to price changes setting up an interface of two incompatible models. Third, the precision with which agricultural models can estimate global land use change and associated GHG emissions, or carbon debt associated with LUC, are so low as to be meaningless.

60. The high level of uncertainty created by model incompatibility and by aggregate agricultural models not capable of capturing necessary refinements in LUC and agricultural management practices has led to two positions on including indirect LUC in LCA models. First, we know that indirect LUC and associated GHG emissions are not zero, so we are doing a disservice to society by not including them in LCA estimates, even though the “confidence interval” is extremely wide (Hertel et al., 2010). Second, we
do not have the tools to obtain a reasonably accurate estimate of the GHG emission effects of indirect LUC, and we are doing a disservice by trying to measure the unmeasurable (Babcock, 2009b).

61. Another issue surrounding LCA involves the inputs to the model. A LCA is only as valid as the data and assumptions used in the model. Analysts are faced with value judgments as to which data, facts, and norms are considered relevant in deriving a single score regarding GHG impacts. With new processes, manufacturing methods, and materials constantly being introduced into production processes and value chains, it is important that data used to perform the LCA are accurate and current.

62. Although there are a number of qualifiers, the same LCA model should be used to derive GHG emission estimates when comparing different feedstocks or different fuels since cross-model comparisons simply highlight model differences (i.e., it is important to create a stable market environment when comparing fuels). Yet, in order to provide a complete understanding of the sensitivity of LCA results and policy impacts to model assumptions, it is important to consider alternative LCA models (and assumptions).
ANNEX A

Partial Inventory of LCA Models

63. LCA models provide comparative analyses of fuel cycle and GHG emission estimates for alternative transportation fuels. Several LCA models, many of which are in the public domain, have been developed for different countries and regions of the world. The LCA models that we review below were typically developed for national or regional analysis, and represent unique country and regional characteristics, including feedstock extraction, biorefinery conversion, transportation infrastructure, vehicle energy efficiency, and transportation modes.

EU platform

64. The EU Platform on LCA was established by the European Commission to promote the availability and exchange of consistent and quality-assured life cycle data and encourage the use of LCA by business and public authorities. To ensure greater coherence across instruments and robust decision support, the Platform supports the development of the International Reference Life Cycle Data System (ILCD), the European Life Cycle Database (ELCD), the International LCA Resources Directory, and includes an electronic discussion forum.

65. The European Commission Life Cycle Thinking and Assessment programme promotes LCA by using a broader approach than those employed by individual private businesses and considered in current government actions. The programme encourages examination of consumption and production behaviours of private business beyond their own product supply chain, and governments beyond their own political boundaries, to consider the impacts or benefits that occur to other companies or regions. Therefore, Life Cycle Thinking is based on the goal of minimising "burden shifting", with a focus on reducing environmental impacts over the whole production process rather than on a specific element within the production process. Figure A1 provides a diagram of the components involved in Life Cycle Thinking.

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The Graz/Oak Ridge Carbon Accounting Model (GORCAM) is a spreadsheet model developed by Bernhard Schlamadinger from the Institute of Energy Research at Joanneum Research in Austria and Gregg Marland from the Oak Ridge National Laboratory in the US to calculate the net fluxes of carbon to and from the atmosphere associated with land management and biomass utilisation strategies. The following factors are considered in the model:

- Changes of carbon stored in vegetation, plant residue, and soil;
- Reduction of carbon emissions when biofuels replace fossil fuels;
- Carbon storage in wood products;
- Reduction of carbon emissions due to wood products replacing energy-intensive materials such as steel or concrete;
- Recycling or burning of waste-wood; and
- Auxiliary fossil fuels used for production of biofuels and wood products.

The GORCAM model relies on a host of parameters which describe the management regime (e.g. harvest cycle, growth rate), the land use before the project, and the way in which the biomass is used for carbon mitigation. Since these input parameters may be difficult to measure and subject to uncertainties, the model outputs may not be accurate and, therefore, should be validated at least for the baseline (Schlamadinger, 2004). Figure A2 provides an overview of GORCAM.

Figure A2. Overview of GORCAM

The model GORCAM (Graz / Oak Ridge Carbon Accounting Model)


FullCAM

67. The Full Carbon Accounting Model (FullCAM) was developed by the Australian National Carbon Accounting System to provide estimates of GHG emissions and removals from land use, land use change, and forestry. By integrating biomass, decomposition, and soil carbon models, FullCAM provides a single model capable of carbon accounting in forest, agricultural, transitional (e.g. afforestation, reforestation, and deforestation), and mixed (e.g. agroforestry) systems. This centralised model avoids omission or double counting which may have arisen when multiple carbon pools and transfers are accounted for independently. FullCAM can be run in a point, estate (a mix of areas by age/activity types), or spatial mode (as fine as a spatial resolution of 1 hectare) that will integrate information drawn from the remotely sensed land-cover-change programme, productivity and climate surfaces, and other ancillary data to perform various accounting routines capable of meeting the various reporting requirements of the UN Framework Convention on Climate Change (i.e. more specifically the Kyoto Protocol).

68. Many input options are at the discretion of the user to reflect management decisions such as forest harvest and cropland plowing. A further set of required inputs determine the empirical rates of

10. See Richards (2001) for more details.
transfer between pools or to the atmosphere. These empirical rates are static and do not change in response to changes in environment. Figure A3 provides an overview of FullCAM.

**Figure A3. Overview of FullCAM**

![Diagram of FullCAM](image)


**GREET**

69. The Greenhouse gases, Regulated Emissions, and Energy use in Transportation model ("GREET") is an Excel-based program developed in 1995 by the Center for Transportation Research at Argonne National Laboratory. Depending on the fuel feedstock, GREET provides a “well-to-wheels” or “field-to-wheels” analysis of transportation fuel production. Figure A4 provides a visual depiction of the components in a “field-to-wheels” analysis. The model can analyse more than 100 fuel production pathways and 75 vehicle/fuel systems using a variety of fuel feedstocks including petroleum, natural gas, nuclear, coal, maize, soybeans, maize stover, herbaceous biomass, sugar cane, woody biomass, forest residue, and farmed trees (Wang, 2007 Presentation).
GREET is primarily used to estimate GHG (i.e. CO$_2$, CH$_4$, and N$_2$O) and other emissions (i.e. VOC, CO, NO$_x$, SO$_x$, PM$_{10}$ and PM$_{2.5}$) impacts of alternative fuels and practices, allowing comparison of the “well-to-wheels” or “field-to-wheels” net energy value (NEV) and GHG reductions from alternative production practices. GREET model estimates have provided GHG comparisons that have been important for comparison studies of alternative transportation fuels, such as biofuels versus conventional gasoline, and therefore, has contributed significantly to recent policy analysis (i.e. CARB, RFS.2). The model allows users the flexibility to adjust several model parameters, including the ability conduct stochastic simulations in order to analyse GHG emissions consistent with production practices and test the sensitivity of the results to alternative production environments. A few limitations of the GREET model include a lack of regional variation in model assumptions, price-responsive land use change and mixed cropping systems, the use of US average inputs, and limited co-product scenarios (Unnasch, 2008).

**BEES**

The Biofuel Energy Systems Simulator (“BEES”) is a software program developed by researchers at the University of Nebraska-Lincoln that analyses the environmental impact, or “cradle-to-grave” LCA, of maize-ethanol production. The BEES model analyses the energy efficiency and GHG emissions from crop production, maize to ethanol conversion, co-product utilization (cattle feedlot), and anaerobic digestion for conversion of manure to biogas (Liska et al., 2008). The software provides users the ability to change key default parameters and explore different maize-ethanol production scenarios.

The model contains three types of analysis: energy analysis (life-cycle net energy yield and efficiency), emissions analysis (net GHG emission and global warming potential), and environmental resource requirements (land, grain, water, fossil fuels, petroleum). The BEES model can also be used to evaluate a local, state, or national biofuel system with default scenarios available for multiple locations and can estimate annual cumulative impacts (Liska et al., 2008). A benefit of the BEES model over previous
LCA models is the use of up-to-date plant technology that accounts for recent advances in maize grain-ethanol production systems. Liska and Cassman (2008) found that accounting for up-to-date refinery efficiency and the use of natural gas for thermal energy established the reduction of biorefinery thermal energy use by 35-57%. Although BESS is limited to maize grain-ethanol production (currently being modified to handle biomass feedstocks), the model incorporates a wider range of energy-related activities within the LCA that are ignored by previous models such as co-product utilization and anaerobic digestion.

**EBAMM**

73. The ERG Biofuels Analysis Meta-Model (EBAMM) is a model developed by researchers at the University of California, Berkeley to provide a simple, transparent, yet flexible tool to analyse alternative biofuel production processes. Farrell *et al.* (2006) introduces the EBAMM model and used the program to make a comparison of the data and assumptions from six previous studies. The flexibility of the EBAMM model allowed the authors to reparameterise the model to simulate previous literature and develop their own estimates based on parameter assumptions. By adding missing parameters and dropping unnecessary parameters, the authors were able to construct consistent system boundaries between previous literature estimates. Analyzing the sensitivity of energy balance estimates to parameter assumptions from previous literature, Farrell *et al.* (2006) found net energy balance to be most sensitive to co-product allocation assumptions (*i.e.* allocating GHG emissions or energy use to co-product production).

74. EBAMM can also be used to compare alternative transportation fuels at each stage of production. Table 1 provides EBAMM CO₂e estimates for the various inputs into the biomass production phase while Table 2 provides coefficients for the biorefinery conversion phase of producing maize and cellulosic (switchgrass) ethanol. These figures, and other potential applications of EBAMM, illustrate the relative GHG emission reductions of alternative biofuels and can be used for policy-relevant analysis. Although EBAMM is very useful in testing the sensitivity of model assumptions and comparing alternative transportation fuels, the model ignores end use technologies and fails to account for all aspects in the biofuel production process, and therefore does not provide a complete life-cycle analysis (Farrell *et al.*, 2006).

75. There are several other recognized LCA models, including LEM, Acurex1996, LBST E3 Database, PWC Ecobalance, SimaPro, and EcoIvent not covered in our discussion. Instead, we have tried to highlight LCA models that are representative of the carbon accounting framework followed by LCA models in deriving estimates of GHG emission comparisons for alternative fuels.
ANNEX B

Partial Inventory of Domestic and Global Agricultural Models

Partial equilibrium models

76. In estimating LUC impacts, three PE models have received significant attention and application to LUC. Each of these models has advantages and disadvantages in the LUC context.

CARD/FAPRI

77. Among the PE models, the Center for Agricultural and Rural Development/Food and Agricultural Policy Research Institute (CARD/FAPRI) modelling system is the most widely used global model. The model contains supply and demand models for all important agricultural products produced in temperate climates for major producing countries. This multi-commodity, international agricultural modelling system uses a set of interrelated supply and demand models to allow the interactions needed to study detailed agricultural land use adjustments in global agricultural markets. CARD/FAPRI utilises this set of interrelated models to estimate the impacts of changes in policy and economic parameters on prices and production for important agricultural commodities in major importing and exporting countries.

78. Advantages include detailed global agricultural and commodity coverage in all major producing regions. Limitations of the model include exogenous economy-wide relationships and LUC limited solely to cropland except in the US and Brazil where pastureland is also considered. Especially when attempting to measure the GHG emission impacts, ignoring pastureland and forestland tradeoffs makes it extremely difficult to develop reasonable GHG estimates. The carbon debt created by disturbing existing land uses is sensitive to the current land use. For example, the carbon debt of converting pastureland to cropland is significantly different than converting rainforest to pastureland. Also, converting pastureland to cropland may induce the conversion of forestland to pastureland. Unfortunately, this level of detail is not included in any global agricultural models used to estimate LUC.

79. Fabiosa et al. (2009) use an updated FAPRI model for “land allocation by type of crop and pasture use for countries growing feedstock for ethanol (corn, sorghum, wheat, sugarcane, and other grains) and major crops competing with feedstock for land resources such as oilseeds.” This update is used to assess impacts of ethanol demand shocks in US, Brazil, China, EU, and India. Forestland tradeoffs are also excluded and GHG impacts are being added to the model. Dumortier et al. (2009) have modified CARD/FAPRI model “to assess impacts of energy price increase and biofuel policy changes on land conversion.” They use GreenAgSim to “evaluate emissions from land conversion and agriculture production and to calculate the GHG implications of agricultural activity.”
FASOM

80. The Forest and Agricultural Sector Optimization Model\textsuperscript{11} (FASOM) is a partial equilibrium economic model of the US forest and agriculture sectors with land use competition and linkages to international trade (Alig et al., 1998). An extension of the FASOM model, the Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOMGHG) includes most of the major GHG mitigation options in US forestry and agriculture, accounts for changes in GHG from most agricultural activities, and tracks carbon sequestration and carbon losses over time (US EPA, 2005). The interaction of the economic and biophysical systems within the FASOMGHG version allows for an accounting of mitigation over time and by region and quantification of leakage effects. Inclusion of non-GHG co-effects provides insight into the multiple environmental and economic tradeoffs related to GHG mitigation.

POLYSYS

81. POLYSYS is another US-based PE model for LUC projections, but it has the advantage of having biomass production alternatives included as cropping options (de la Torre Ugarte et al., 2009). Thus, this model has been used to estimate the potential production of cellulosic ethanol under different biofuel and carbon scenarios and is designed to estimate land use allocations in response to the RFS2 mandate. It does not have GHG emissions built into the model. Like the FASOM model, POLYSYS contains significant detail on US agriculture and is only capable of capturing LUC land use changes for the US.

82. There are two other PE agricultural models that can also be used to estimate LUC although published applications of these models to LUC are not as readily available in the literature. The two models were developed by the International Food Policy Research Institute (IFPRI) and the International Institute for Applied Systems Analysis (IIASA). Both of these models originally were developed around longer run assessments or visions of what world leaders need to do to feed growing world populations, reduce malnutrition and poverty, and protect and enhance the productivity of the natural resource base and rural areas. There have been less published applications of these models to shorter run LUC responses to national and regional agricultural and biofuel policies and programmes.

IMPACT

83. The IMPACT model is designed to examine alternative scenarios for world supply, demand, prices, trade, and food security for agricultural commodities at the global level. The model accounts for most of the world’s food production (30 commodities) through 115 sets of demand and supply equations, as well as linked agricultural trade among the countries. The IMPACT model also has embedded land use coefficients to endogenously estimate LUC impacts as commodity demands, supplies, and prices adjust. The model also has a link Water Simulation Model (WSM) to determine the interactions between water supply and demand and food demand, supply, and trade. The WSM is unique to IMPACT and is particularly useful in estimating future climate change impacts on food security. This model has been used to develop longer run global food projections and the implications for food security. The model focuses on cropland but does allow for exogenously determined land conversion trends in addition to LUC do to endogenous commodity price changes in the model. The model was used in the 2008 food-fuel debate to determine the impact of biofuel expansion on food prices (Rosegrant (2008). Compared to the other studies reported at that time, IMPACT reported a significantly greater impact of biofuel expansion on food price. In part, this may be the result of the longer run of the model and the way that LUC is tied to an exogenous trend component.

\textsuperscript{11} See US EPA (2005, Chapter 3) for more details.
IIASA Model

84. The IIASA Land Use Change and Agricultural Program (LUC) goal is to support policy makers in the evaluation of realistic national and regional strategies for the production of food, feed, and bioenergy while sustaining land and water resources, sustaining food security, and promoting rural development. To this end, combining the IIASA integrated system for ecological-economic analysis for food and agriculture development with the FAO-IIASA AEZ system for spatial analysis of cropland used to produce food, feed, and energy crops, appears to be the most appropriate approach. The world food system model or Basic Linked System (BLS) can be link to downscaling and upscaling models to achieve lesser or greater statistical detail including the agro-ecological zones (AEZ) modelling framework for assessing agricultural and bioenergy tradeoffs. The model has been used in studies pertaining to biofuels, food security, and sustainability. For example, the recent issue of *Biomass and Bioenergy* (2010) reported integrated analyses carried out in the EU’s REFUEL Project. The IIASA modelling framework provided the quantitative results for the land use dynamics for food, feed, and biofuel subject to constraints on food production, nature conservation, and ecological preservation, and how the results relate to increasing land productivity in Eastern Europe and second generation biofuel development. Documentation of the actual IIASA model and framework is not readily available, so specific framework characteristics are not included in this report. The IIASA model framework also has a Global Forest Sector (G4S) Model that allows for trade between countries in a variety of forest products. If this model can be linked to the LUC modelling framework, a global treatment of LUC impacts for both agriculture and forestry may be attainable in the future.

GLOBIOM

85. The Global Biomass Optimization Model (GLOBIOM) is a global recursive dynamic partial equilibrium model that integrates an agricultural, bioenergy, and forestry sectors. An application of the model is to provide policy analysis on global land use competition between major land use sectors. The model is similar in structure to and draws upon other global agricultural and forestry models for various components (Havlik et al., 2010). Havlik et al. (2010) use GLOBIOM to evaluate the implications of first and second generation biofuel targets on global land use.

Computable General Equilibrium and Integrated Assessment models

86. There are several CGE and variants of the GTAP model that have been developed for both global, regional, and country analysis. Unlike many of the PE models which have been developed to address a variety of agricultural and biofuel policy shocks, the CGE models are frequently more specialized with respect to a sectoral emphasis or analysis and the specific policy shock under consideration be it trade, biofuels, or agricultural policy.

GTAP

87. The basic Global Trade Analysis Project (GTAP) model is a global CGE model with multiple, bilateral trading sectors. The model allows users to adjust various model parameters in order to analyse policy scenarios in a general equilibrium approach. GTAP incorporates a global banking sector to control global savings and consumption that has been modified to allow analyses of emerging social and political scenarios. GTAP-E is an extension to the basic GTAP model that incorporates energy substitution and allows analysis of fossil fuel consumption and carbon emissions changes from climate mitigation policy, including the potential to trade emissions internationally (Burniaux and Truong, 2002; Birur et al., 2008; Hertel et al., 2010).
88. The GTAP-BIO model, which incorporates a biofuel sector into the GTAP-E model, is outlined in Birur et al. (2008). GTAP-BIO accounts for the production and consumption structure of biofuels and allows substitution of biofuels for petroleum products. Keeney and Hertel (2009) utilise the GTAP-BIO model to estimate the indirect land use impacts of US biofuel policies on land in both the US and rest of the world while accounting for varying yield and mobility (trade) assumptions. To analyse the relationship between GHG emissions and global land use in agriculture and forestry, Golub et al. (2008) introduce GTAP-AEZ-GHG, which captures the opportunity cost of land use decision, accounts for heterogeneity in land types across and within sectors, and allows input substitution between land and other factors of production.

89. The GTAP model is useful for policy analysis but the limitations and assumptions of the model need to be considered when interpreting model results. The basic GTAP model assumes perfect competition and constant returns to scale. Babcock and Carriquiry (2010) provide an analysis of the shortcomings and applicability of the GTAP model, including the restricted cross-price elasticities due to functional form assumptions, model assumptions that are not consistent with current empirical evidence, and lack of accounting for double-cropped acres and availability of idle land for agriculture production. Despite limitations which are possessed by shortcomings, the GTAP models provide global trade implications from current and potential climate mitigation policies in the context of economy-wide feedback loops.

Integrated Assessment Models

90. Integrated Assessment Models (IAM) are typically detailed sector models that are linked to or coupled with CGE models to provide more country, sector, and environment detail. A more detailed and comprehensive assessment of different CGE models and associated IAM modelling efforts along with their strengths and limitation can be found in Platanik and Roson (2009). The authors provide a useful comparative table on recent CGE and IAM model applications, which is provided in Annex Table B1.
### Annex Table B1. Recent CGE model applications

<table>
<thead>
<tr>
<th>Modeling Framework</th>
<th>Reference</th>
<th>Temporal resolution and coverage</th>
<th>Spatial resolution and coverage</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>GTAPE-L</td>
<td>Burniaux and Lee (2003)</td>
<td>Comparative static; base-year 1997</td>
<td>5 regions; Global</td>
<td>Exemplify the incorporation of land/land use in GTAP; assessing GHG mitigation policies with focus on land-use impacts</td>
</tr>
<tr>
<td>GTAP-AGr</td>
<td>Keeney and Hertel (2005)</td>
<td>Comparative static; base-year 1997</td>
<td>23 regions, global; 5 agricultural sectors</td>
<td>Assess the implications of multilateral changes in agricultural policies</td>
</tr>
<tr>
<td>CGE for Canada</td>
<td>Robidoux et al. (1989)</td>
<td>Comparative static</td>
<td>Canada</td>
<td>Analyze Canadian farm policies</td>
</tr>
<tr>
<td>CGE for Philippines</td>
<td>Abdula (2005)</td>
<td>Comparative static</td>
<td>Small open economy Philippines</td>
<td>Study the conflict between food and bio-fuel production</td>
</tr>
<tr>
<td>GTAP-based CGE for</td>
<td>Ignacik (2006, chapter 5)</td>
<td>Comparative static</td>
<td>Small open economy (Poland)</td>
<td>Explore the potential of biomass as a source of energy</td>
</tr>
<tr>
<td>Poland</td>
<td></td>
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<tr>
<td>GTAPEM</td>
<td>Hsing et al. (2004), Brooks and Dewbre (2006)</td>
<td>Comparative static; 2001-2020</td>
<td>7 regions, global; 8 agricultural sectors</td>
<td>Analyze the impact of agriculture and non-agriculture reform, with a particular focus on the effects of OECD agricultural policy on developing countries.</td>
</tr>
<tr>
<td>GTAP/Supply Curve</td>
<td>Baltzer and</td>
<td>Comparative</td>
<td>22 regions global; 15</td>
<td>Analyze changes in global wheat supply and</td>
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(continued on next page)
<table>
<thead>
<tr>
<th>Model</th>
<th>Model Description</th>
<th>Number of Regions/Worlds</th>
<th>Focus</th>
</tr>
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<tbody>
<tr>
<td>FARM</td>
<td>Darwin et al. (1996)</td>
<td>Comparative static, 1990-2090</td>
<td>Multi-scale: 8 regions world 0.5 lon/lat, Integrate explicit land and water assessment into CGE, environmental focus on climate change</td>
</tr>
<tr>
<td>GTAP-AEZ</td>
<td>Lee (2004), Lee et al. (2009)</td>
<td>Comparative Static, 2001</td>
<td>8 agricultural sectors + forestry, 3 world regions</td>
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<tr>
<td>GTAP-Dyn/AEZ modified for land use analyses</td>
<td>Golub et al. (2006)</td>
<td>Recursive dynamic 1997-2025</td>
<td>11 regions, global</td>
</tr>
<tr>
<td>GTAP-Dyn and Global Timber Model</td>
<td>Golub et al. (2009)</td>
<td>Recursive dynamic 1997-2025</td>
<td>11 regions, global</td>
</tr>
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</table>

2. Integrated Assessment Models

<table>
<thead>
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<th>Model</th>
<th>Model Description</th>
<th>Number of Regions/Worlds</th>
<th>Focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>GTAP-LEI/IMAGE coupling within EURURALIS</td>
<td>Klijn et al. (2005)</td>
<td>10-year steps; 2001-2030</td>
<td>Multi-scale: national level, sub-national level (NUTS2), grid level; Global with focus on EU15</td>
</tr>
<tr>
<td>KLUM@GTAP</td>
<td>Ronneberger et al. (2009)</td>
<td>Comparative static, 1997-2050</td>
<td>16 regions, Global, 4 agricultural out of total 17 sectors.</td>
</tr>
</tbody>
</table>

Source: Palatnik and Roson (2009).
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