To: John Courtis (California Air Resources Board)
From: Alex Farrell
Michael O'Hare
RE: Greenhouse gas (GHG) emissions from indirect land use change (LUC)
Date: January 12, 2008
cc: UC LCFS team, Tim Olson (California Energy Commission)

There is no well-accepted value for the greenhouse gas (GHG) emissions due to changes in land use because of increased biofuel production (called indirect LUC emissions).[1] Several independent efforts are now underway to estimate these effects, including:

1. UC Davis project sponsored by ARB (Mark Delucchi, Principal Investigator). This is a continuation of research that has been ongoing for several years.[2]
2. US EPA analysis using FASOM-GHG and FAPRI. This project was begun in 2007 to support the President's "20 in 10" initiative, but has been re-directed to support rulemaking for the 2007 Energy Bill.
3. Various researchers at universities and research institutes in the U.S. and Europe.

None of these studies are yet available, but the analysts are taking varied approaches that will yield a range of results. These calculations are difficult and demand subjective judgments about methods and parameters, so disagreements about these values may continue for a long time. However, with Rich Plevin and Andy Jones, we estimated the upper bound of indirect emissions using recently published estimates comparing biofuel production and LUC.[3,4] The attached spreadsheet shows these calculations. **These are crude upper limit estimates and once better estimates (e.g. those above) are available, the values presented here should be abandoned. Future research may find higher or lower values for several reasons:**

- Yields from biofuel crops grown on newly cultivated land may be higher (initially at least) or lower (because new lands are presumably less productive than those currently cultivated for a given crop). Lower yields mean the emission figures in this spreadsheet are generally too low.
- Crops on marginal lands may require extra inputs of (for example) fertilizer, with higher continuing production emissions.
- Improved biofuel production technology may improve fuel yield per unit of crop and therefore per hectare.

[1] See the UC LCFS report Vol 1. pp. 39-44 and Vol 2 64-67. Note that in formal economic modeling, often no distinction between direct and indirect emissions is made. However, in terms of public policy, GHG emissions are currently identified with the jurisdiction (state, nation, etc.) in which they occur, so the difference between direct and indirect is still relevant.

[2] See http://www.its.ucdavis.edu/people/faculty/delucchi/index.php

[3] Righelato and Spracklen (2007) "Carbon mitigation by biofuels or forests?" *Science* 317: 902

[4] Reijnders and Huijbregts (2008) "Palm oil and the emission of carbon-based greenhouse gases." *Journal of Cleaner Production*. 16: 477-482.

Alexander E. Farrell
Associate Professor, Energy & Resources Group
Director, Transportation Sustainability Center
http://erg.berkeley.edu/erg/people/faculty/farrell.shtml

- Diversion of food crops (such as corn) into ethanol will be partly accommodated by reduced meat consumption and partly by increased crop yields, which would indicate less than a hectare-for-hectare induced effect. The share of accommodation among less consumption of feed grains (price elasticity effect), increased grain yields (intensive margin effect), and land use conversion to produce more grain (extensive margin effect), requires economic modeling not yet available.[5]

However, we do not expect better analysis to change the overall result that land use change will be a found to be *very large contributor* to the global warming impact of the biofuels evaluated here. How best to account for this effect in the LCFS is less clear.

The first sheet (Assumptions) shows the values taken from the peer-reviewed literature, as well as various other assumptions. The second sheet (Direct Conversion Emissions) uses these values to calculate the direct emissions assuming one hectare (ha) of land in biofuel feedstock production leads to exactly one ha of land undergoing the indicated land use change (e.g. tropical forest being converted to sugar cane in row 7). These values are then used in the third sheet to investigate the magnitude of potential implications for carbon intensity. The first page (columns A-J) of the third sheet simply repeats the calculations we did for the August 2007 report. The second page (columns L-Q) first shows my estimates of the carbon intensity from the State Alternative Fuels Plan (rows 1-1).[6] These values are very similar to our August 2007 report.

The direct LUC emissions are shown next (column N, rows 15-27) are really enormous, much larger than the emissions associated with fuel production itself. These emissions are those associated with the one-time change in land use shown in column L, spread over the time period shown in column P, based on the low/mid/high scenario from Righelato and Spracklen (2007), shown in column O. So, for instance, if we assume that one kg of corn used for ethanol production each year has induced conversion of land from temperate grassland (as in the Conservation Reserve Program-CRP) to corn production, the LUC indirect emissions due to this effect are about 140 g/MJ annually for 20 years, using the mid-range scenario.

Note that this value is *very* different from the estimate currently used in GREET, 0.9 g/MJ (N15).[7] The GREET model (version 1.5) has a limited accounting of the effects of land use change on the carbon cycle. In the GREET documentation, the calculation of CO_2 emissions related to land use change is dependent mainly on two factors: fractions of an acre of pasture land converted to cropland per acre of corn planted, and the change in CO_2 emissions resulting from converting pasture land to cropland. The first parameter, pasture land converted per acre of corn, is assumed to be about 0.5. The second parameter, the CO_2 emission rate from converting pasture to cropland, is based on a personal communication from Mark Delucchi to Michael Wang (Wang, 1999, p. 79) and is more than an order of magnitude lower than Delucchi's current estimates. As a result of these two assumptions, GREET estimates that CO_2 emissions from land use change are almost certainly far too low.

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[5] Performing such economic modeling is a major priority of research in this area, however methodological challenges and data uncertainties prevent an easy answer.

[6] CEC-600-2007-004-REV

[7] See http://www.transportation.anl.gov/software/GREET/index.html

One interpretation of these calculations is that ethanol produced from corn grown on former CRP land has 2.4 times the GHG emissions of gasoline (Q17), an interpretation that assumes no indirect effects, just the direct effect of converting grassland. As you can see, including indirect LUC may have an even greater effect, although the values shown here are rough upper bounds because they assume that one acre of corn for ethanol production leads to one acre of deforestation. (Also, note that land use change is happening due to other factors as well, such as increasing meat consumption worldwide. The changes described here *in addition to* those emissions.)

The reason for considering tropical forests is that this is where much of the expansion of agriculture is occurring worldwide. A key feature of indirect LUC emissions is that they *cannot* be attributed to any particular acre of crop production or batch of biofuel because they are a result of global markets for energy and food. There may be several steps involved, such as 1) a shift on a one hectare plot of land from corn/soy rotation, leading to 2) lower U.S. soy exports, leading to 3) increases in world soy prices, leading to 4) conversion of (for instance) cattle grazing land in Brazil to soy, leading to 5) conversion of Amazonian rainforest (whether legal or not) to cattle grazing land. The net effect is more land in corn production and less land as rainforest. There is no way around this effect unless we un-make the global economy. Simply said, ethanol production today using U.S. corn contributes to the conversion of grasslands and rainforest to agriculture, causing very large GHG emissions. Thus, indirect LUC emissions must be applied to *all* biofuel production that uses crops grown on arable land. Uncertainties exist in how to calculate the size of this effect and how to attribute it to biofuel.

The value for palm-based renewable diesel is worth pointing out because the conversion of tropical forest to palm plantation is a *direct* effect. The current version of GREET-California ignores this effect entirely (as well as any land use change induced by sugar cane production). Therefore, it is appropriate to simply add the entire direct LUC GHG emission estimate, which means that palm oil-based renewable diesel has over twice the GHG emissions, based on the calculations provide in the attached spreadsheet.

Rows 23-27 show some of the uncertainty in the calculation of GHG emissions from indirect LUC due to corn ethanol production, giving a range of values for conversion the rainforest to corn production. Unsurprisingly, given the state of current knowledge, the results give an order of magnitude result, from 84 g/MJ to 830 g/MJ.

This analysis suggests that indirect GHG emissions are *larger* than direct, due to the large amounts of carbon stored in ecosystems of all sorts. The simple sensitivity analysis shown on rows 39-50 suggests that even if only a small fraction of the emissions calculated in this crude way are added to estimates of direct emissions for corn ethanol, total emissions for corn ethanol are higher than for fossil fuels. The same is also true for sugarcane-based ethanol. This is problematic for Califorinia’s GHG goals under AB32, which are pegged to emissions in 1990, when there was little ethanol in our fuel. The key implication is that deciding how to calculate indirect LUC emissions of GHGs, and if and how to apply these values to biofuels will have major implications for the LCFS and AB32 goals. Scientific and policy debates about these issues are underway in Europe as well as in the United States, and probably elsewhere as well.

Several other implications emerge as well. First, if indirect emissions are applied to the ethanol that is *already* in California's gasoline, the carbon intensity of California's gasoline increases by 3% to 33%. This is shown in rows 30-39 of the second page. These percentage increases are so large because the GHG emissions from tropical deforestation are very large.

Second, many strategies for firms to use to comply with the LCFS, including replacing current crop-based biofuels with fuels derived from wastes or other feedstocks, do not induce land use change. Reductions in GHG emissions from oil production and refining is also a viable strategy, as are the use of electricity or (possibly in the long run) hydrogen as transportation fuel.

Third, advances in biofuel technologies will most likely create new compliance options as well. Advanced corn ethanol technologies, such as those in use today at the E3 plant in Mead, Nebraska (though E3's recent bankruptcy casts a shadow over this approach), or under construction at the XL biorefinery in Vicksburg, Arizona, may allow corn ethanol to be used to lower the carbon intensity of fuels in California.[8] Ethanol (or other blendstocks) from cellulosic feedstocks, which may provide very high per-hectare yields in the future, or from crops that do not otherwise change land use (such as winter cover crops) or biofuels that do not cause LUC, such as fuels made from wastes and residues, may also be economically and technically possible in the near-to-medium future.

[8] See http://www.e3biofuels.com/ and http://www.d2-webdesign.com/xldairy/index.html