Corn oil biofuel land use change emission impacts: sharing emission savings between ethanol and biodiesel


The results obtained from these simulations indicate that extracting corn oil reduces the induced land use emissions due to total biofuel production. . . . The bottom line is that more biofuel is produced from the same or fewer land resources, so total system land use emissions fall.

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Keywords: corn oil biodiesel - land use impacts - reduced fat distiller grains - computable general equilibrium - global economy

Recently, US corn ethanol producers, using a new technology, began extracting corn oil from their distillers’ dried grains. Corn oil can be and is used to produce biodiesel. We examine the extent to which this technology can help the US to achieve its biofuels targets with lower induced land use emissions. We conclude that the answer depends on how the reduced emissions are credited – to the ethanol, to biodiesel, or to the corn oil itself. The new technology is introduced into the GTAP-BIO model, a computable general equilibrium model that has been frequently used for estimating biofuel-policy-induced land use changes. Then induced land use emissions due to ethanol and biodiesel are calculated from the estimated land use changes with and without using the new technology. The allocation method chosen for corn oil can have important impacts on the estimated land use change emissions. Generally the impacts on corn ethanol are similar regardless of the approach taken, but soy biodiesel can vary significantly according to the approach taken.

Ethanol production has increased from about 1.6 billion gallons (BGs) in 2000 to 13.3 BGs in 2013 in the United States [1]. Most ethanol in the US is produced from corn. Corn ethanol can be produced through dry and wet milling processes. However, the majority of US ethanol plants use the dry mill process [2]. This technology converts corn to two main marketable commodities: ethanol and distillers’ dried grains with solubles (DDGS). More recently ethanol producers have introduced a new technology that extracts corn oil to produce an additional marketable product. About 192 pounds of corn oil is produced per 1000 gallons of ethanol [2,3]. The industry has evolved from no corn oil extraction in 2001 to 33% in 2008 and 78% in 2012 [2,4].

The nutritional values and physical quality characteristics of the reduced fat DDGS is not exactly identical to the conventional variety. However, there is now some research that indicates that the new lower fat DDGS may have approximately the same market value as conventional DDGS [5–8]. Recent trends in DDGS to corn price ratio supports this argument. Figure 1 shows the DDGS to corn price ratio from September 2007 through September 2014. The price ratio varied between 0.8 and 1.0 through 2012, went up in 2013 with increased export demand and is now back around 1.0. Even though the fraction of corn oil extraction in total ethanol roughly tripled over this period, there is no perceptible price trend.

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We also consulted industry DDGS marketing experts who indicated that today high fat (no corn oil extraction) and DDGS with corn oil extraction with 7% fat remaining in the product are priced about the same. These experts also indicated that a few plants use a technology that leaves only 4% fat in the DDGS product. They estimated this product would sell at about a $10/ton discount because of the reduced fat. However, the 7% fat product is the new standard, and it has no price discount. Since GTAP is driven by market values, and both the data and industry experts suggest price is the same for both high fat and moderate fat products, we took that approach. It is also important to note that extracting oil from DDGS reduces the output of DDGS by the amount of extracted oil. So our assumption that the new product has about the same market value as the old product is validated both by historic price relationships (Figure 1) and by industry experts.

While the market values of the reduced fat DDGS and conventional DDGS are similar, the new processes helped the corn ethanol industry to be more efficient and generate a new valuable product: corn oil. The extracted corn oil can be used for multiple purposes, including as a biodiesel feedstock. Oil can be extracted before the corn is processed (front-end) or after the processing (back-end). The back-end method is less expensive and used by most ethanol producers in the United States. The back-end extracted corn oil cannot be used for food purposes, which is one reason much of it is used for biodiesel.

While the extraction of corn oil through the production process of ethanol has directly helped the ethanol producer to increase profitability, it has important indirect benefits as well. The extracted oil can be used to produce biodiesel. The conversion rate of corn oil to biodiesel may differ from one producer to another and could be slightly different from the corresponding rate for soybean oil in general. Given the high level of ethanol production, the volume of extracted corn oil is large. When this corn oil is used for biodiesel production, it reduces the amount of oil from other sources required to achieve any given level of biodiesel production. Even if the extracted oil is consumed in other uses, it could free up other fats and oils for biodiesel production. This substitution could reduce the land use impacts for any given level of combined ethanol and biodiesel production. The major objective of this paper is to assess this effect.

In recent years, several studies have been carried out to evaluate the induced land use changes due to corn ethanol production [9-13]. These studies, regardless of their modeling frameworks, traditionally, assume that the ethanol producers only produce the two commodities—ethanol and DDGS. Since most of the US ethanol industry is extracting corn oil, it is important to revise the traditional assumption and include the new product in the basket of commodities produced by the ethanol industry. Having done that, we can then examine the land use consequences of ethanol production with this additional product in the mix.
Life cycle analysis (LCA) is usually categorized as attributional or consequential. Attributional LCA evaluates the life cycle consequences of a given production system within its system boundaries. Consequential LCA evaluates the consequences of implementing a production technology or policy. In this approach the consequences can go far beyond the production system [14]. Consequential LCA is often used to evaluate government policies mandating some particular technology such as biofuels [15]. Thus, consequential LCA uses as its system boundary the entire domain of consequences of any given policy – such as the US Renewable Fuel Standard [16] or California Low Carbon Fuel Standard [17]. Computable general equilibrium models such as GTAP [18] are used in conjunction with attributional models such as GREET [19] to perform the consequential analysis required for regulations.

In what follows we first review the GTAP-BIO model and its major recent developments in the biofuel areas. Then we outline the steps that we followed to introduce corn oil into the GTAP-BIO model. The following section explains the experiments designed to examine induced land use changes due to corn ethanol production in the presence and absence of corn oil. Then the simulation results are discussed. The final section presents our conclusions.

**Background of GTAP-BIO Model**

GTAP-BIO is a global CGE model that handles production, consumption, and trade of biofuels along with other economic activities, and which is capable of tracing the land use impacts of expansion in biofuels. This model is a special version of the GTAP standard model [18] which is designed, intensively modified, and frequently used to assess indirect or induced land use change (ILUC) due to biofuels. ILUC occurs because governments mandate the use of biofuels, which increases demand for biofuel feedstocks and which, in turn, increases their prices and induces farmers anywhere in the world to convert pasture or forest to cropland. The development of this model began with introducing the first generations of biofuels (grain ethanol, sugarcane ethanol and biodiesel) into the GTAP data base version 6, which was representing the global economy in 2001 [20]. Then the first version of the GTAP-BIO model was developed [21] by introducing these biofuels into the GTAP-E model [22,23], which was originally designed to assess regional economic and environmental impacts of national and multinational energy-economy-environmental-trade policies. This first version of the GTAP-BIO model and analyses made based on that version were missing the fact that biofuels are produced in conjunction with their by-products. Taheripour et al. [24] introduced the biofuel by-products and new demand system for animal feed products into the GTAP-BIO model and showed that the models with and without biofuels by-products provide totally different pictures from the global economic and land use consequences of biofuel production. The biofuel by-products mitigate adverse economic impacts of the global biofuel mandates and reduce land use consequences of biofuel production. Then Hertel et al. [25] used this model and examined the effects of US corn ethanol on global land use and greenhouse gas emissions. While, these authors showed that the US corn ethanol program has important land use implications at the global scale, their estimates for the land requirement for ethanol production was only about 0.29 hectares of cropland per 1000 gallons of ethanol, a figure far below 0.73 hectare of cropland per 1000 gallons of ethanol reported by Searchinger et al. [26].

The early versions of the GTAP-BIO model used in Hertel et al. [25] and earlier used the GTAP 2001 database and assumed that: (1) the productivity of new land converted to cropland is 2/3 the productivity of existing cropland all across the world, (2) the land transformation elasticity among forest, pasture, and cropland is about 0.2 all across the world, based on an old evidence from the US economy, and (3) the land transformation elasticity among crops is about 0.5, again all across the world. CGE models typically use Constant Elasticity of Transformation (CET) functional forms to define their land supply system. Land transformation elasticities are needed to define a land supply system. These elasticities govern land allocation among alternative land uses.

Tyner et al. [27] continued to use the 2001 database but made major changes in the early version of the model. First, based on the observed pattern and available data in US and Brazil, they introduced cropland pasture into the land nesting structure of the model to allow farmers to convert their cropland pasture to crop production. Second, they used a new set of land margin parameters. In the old version of the model, all converted land anywhere in the world was assumed to be two-thirds as productive as existing cropland. Clearly, this was not the case. Based on the work done by Taheripour et al. [12] a set of new land margins were introduced in the model. The new land margins reflect the productivity of converted land based on net primary productivity in each area. Finally, they improved the feed demand system to capture the substitution among traditional feed crops and biofuel by-products more accurately. With these changes Tyner et al. [27] showed that about 0.22 hectares of land is needed to produce 1000 gallons of ethanol. They also showed that with an updated base line database for 2006, the size of land requirement decreases to about 0.14 hectares per 1000 gallons of ethanol.
Then Taheripour et al. [28] shifted to the 2004 GTAP base, introduced second generation of biofuels into the model, and changed the land transformation elasticity among crops from 0.5 to 0.75 to ease land transformation among crops in response to changes in relative crop prices based on recent observations showing that many farmers shifted their land from other crops to corn and soybean production. In a more recent paper Taheripour and Tyner [11] altered the land supply tree of the GTAP-BIO model by putting cropland and pasture land in one nest and the combination of these two items with forest in another nest to represent the fact that converting pasture land to cropland is easier than converting forest to cropland. In addition, these authors developed a set of new regional land transformation elasticities according to recent observations on land allocation all across the world and substituted those for the old uniform elasticities. The results of this research show that: (1) the US corn ethanol encouraged farmers to switch to corn and soy from other crops all across the world, (2) about 0.11 hectares of land is needed to produce 1000 gallons of ethanol, (3) ethanol production mainly increases demand for new cropland outside the US, and (4) less forest is converted using the new nesting structure.

The estimated land requirements for corn ethanol obtained from different modeling practices are presented in Figure 2. As shown in this figure the latest estimate for land requirement obtained from the GTAP-BIO model [11] is about 0.11 hectares of new cropland per 1000 gallons of ethanol. This figure is much smaller than the initial figure estimates by Searchinger et al. [26]. Wicke et al. [29] communicated a similar trend in induced land emissions due to biofuels among a wider range of research conducted in this area.

In order to go from estimated land use changes to changes in emissions, an emission factor model must be used to convert the regional land use changes to estimated emissions. If we combine the induced land use changes due to corn ethanol obtained from the latest version of the GTAP-BIO model with the California Air Resources Board (CARB) [30] carbon emission factors and include emissions due to using cropland pasture for crop production based on the CARB assumption, then we get about 13.3 g CO$_2$eMJ$^{-1}$ which is about 13.3% of the initial estimated figure (100 g CO$_2$eMJ$^{-1}$) reported by Searchinger et al. [26]. If we use the Woods Hole (WH) emission factors, then the calculated emissions (including emissions from cropland pasture) would be about 9.1 g CO$_2$eMJ$^{-1}$. The WH emission factors measure soil and vegetation carbon fluxes due to conversion of natural land to cropland per hectare by region. These emission factors are frequently used to evaluate induced land use emissions due to biofuel production [30, 31].

All research studies that examined the effects of US corn ethanol on global land use and greenhouse gas emissions have modeled a production process that produces ethanol and DDGS as a by-product. As mentioned earlier, more recently the ethanol producers...
are producing ethanol, DDGS, and corn oil jointly. According to the research conducted by Christianson & Associates [3] the oil extraction rate, for ethanol producers who use the back end technology to extract corn oil from DDGS, ranges from 0.27 pounds to 0.78 pounds of corn oil per bushel of corn converted to ethanol with an average of 0.52 pounds. This is in line with data from the Mueller [3] corn ethanol survey of 0.53 pounds per bushel. This means that producing 1000 gallons of ethanol generates about 192 pounds of corn oil. Given the large magnitude of ethanol production, the total amount of extracted corn oil by ethanol producers will be a big number. For example, if we assume that all ethanol producers extract corn oil through their production process, then producing 15 billion gallons of corn ethanol (the mandated level of conventional ethanol for 2015) will generate about 2.88 billion pounds of corn oil. This amount of corn oil can be used for biodiesel production to achieve a portion of biodiesel mandate with no induced land use change. The original biodiesel mandate was 1 billion gallons per year, but that was increased to 1.28 billion gallons in 2013 [32,33]. The availability of corn oil means that the US biofuel mandate can be achieved with lower land use emissions.

In addition to the changes explained above, over time we disaggregated the standard GTAP crop sectors to represent more crop categories in our modeling framework and databases to be able to examine induced land use changes for a wide range of biofuel pathways according to their feedstocks. The most recent version of the GTAP-BIO model can evaluate induced land use changes for US corn ethanol, US sorghum ethanol, Brazilian sugarcane ethanol, EU wheat ethanol, EU sugar beets ethanol, and biodiesel produced from soybeans, rapeseed, palm oil, and other oil types of oil and fat in the US and EU.

## Modifications in the GTAP-BIO model and its database

To introduce corn oil into the GTAP-BIO modeling framework, we begin with the model used in [11]. This model carries almost all major changes made in the GTAP-BIO model over time where adequate data are available to use. The main aspects of the model developed and used in the present paper are as follows.

- The base year is 2004.
- Crop products are aggregated into the following categories: paddy rice, wheat, sorghum, other coarse grains, soybeans, palm, rapeseed, other oilseeds, sugar crops, other crops. In addition, a new sector uses cropland pasture to provide feed for the livestock industry. Converting cropland pasture to other crops reduces livestock sector production and increases demand (directly and indirectly) for other feed items through a demand system for animal feeds. In this model, a sector that represents government services holds retired lands under the CRP program.
- Cropland pasture can be converted to crop production if needed, but no change is permitted in the area of CRP land.
- The model uses regional land margins, which measure productivity of new cropland versus the existing cropland developed by Taheripour et al. [12].
- The corn ethanol industry produces three commodities: ethanol, DDGS, and corn oil.
- Possible biofuels included in the model are: corn ethanol, ethanol from sorghum, ethanol from sugar crops, soybean biodiesel, rapeseed biodiesel, palm oil biodiesel, and other biodiesel. The industry that produces other biodiesel uses the extracted corn oil through ethanol production as a feedstock.
- By-products presented in the model are: DDGS produced with corn ethanol, DDGS produced with sorghum ethanol, soybean meal, rapeseed meal, palm meal, and other meals. In addition, corn oil produced by the corn ethanol industry is included. In constructing our database, we reduce the quantity of DDGS produced by the quantity of oil extracted.
- The model uses a multi-level nested demand structure which models demands for alternative feed items for the livestock industry. This nesting structure takes into account direct and indirect substitution among feed ingredients including different types of grains, oil seeds, meals, DDGS, processed feed, etc., in response to changes in feed prices at an aggregated national level. The livestock sectors respond to the changes in relative feed prices and alter the mix of inputs to minimize their production costs. In this process the replacement rate between corn and DDGS (change in corn used over change in DDGS used) may vary according to the changes in relative prices of all feed ingredients. The replacement rate between corn and DDGS could be more or less than one. It is important to note that the feed demand system in an aggregated CGE model such as GTAP, which traces demands for feed items at a national level, is different from a feed demand system at a farm level. For details see [10,24].
- Following TT, the land cover component of the land supply tree uses a two-level nesting format. At the very bottom level of this tree, forest is combined with the bundle of cropland and pasture, and at the higher level cropland is combined with pasture land.
- The model uses the tuned regional land transformation elasticities developed in TT, except for Brazil. TT has defined four groups of very low, low, high, and very high levels of land transformation rates and
then assigned the GTAP regions into these groups according to their recent historical performance in cropland expansion.

- Following Tyner et al. [34], the model is augmented with a module that assumes final consumers and also producers substitute one type of vegetable oil with another type in response to changes in the relative prices of vegetable oils in their demand systems.

To incorporate corn oil as a by-product of the ethanol industry we assumed that ethanol producers obtain the required capital equipment to extract corn oil from DDGS and that the capital costs will be recovered from revenues obtained from selling the extracted corn oil to the industry, which produces other biodiesel. We assume that the entire produced corn oil by the ethanol industry will be used to produce biodiesel. However, it would not make much difference if some of the corn oil substituted for other vegetable oils. In the new model, the other biodiesel industry can use either vegetable oil produced from other vegetable oils (including all types of oils and fats excluding soybean oil, rapeseed oil, and palm oil) or corn oil produced through converting corn to ethanol.

We assigned a relatively high elasticity of substitution among the alternative oils that can be used in the other biodiesel production process to facilitate using produced corn oil in the biodiesel production process. Finally, following the recent evidence presented by Christianson & Associates [11] we assumed that each bushel of corn converted to ethanol on average generates about 0.52 pounds of corn oil and that this process reduces production of DDGS by the same weight. We made all proper changes to maintain the GTAP data (including regional input–output tables) in balance.

The extraction of corn oil from DDGS is a recent development. However, since our database represents the world economy of 2004, we need to introduce the new technology in our 2004 database to be able to assess its induced land use changes. To accomplish this, we assumed that the entire US corn ethanol industry uses the new technology. Therefore, the newly reconstructed base data introduces some corn oil produced from the 2004 level of corn ethanol production. GTAP, like any CGE model, cannot grow a sector from nothing. Therefore that assumption is made to shock the model for future corn ethanol expansion including corn oil extraction.

Table 1 compares the US biofuel production included in the traditional and new GTAP-BIO database. Both models contain identical figures for each biofuel except for other biodiesel. The quantities of other biodiesel in the traditional and new databases are about 2.8 million gallons (MGs) and 89.8 MGs, respectively. The difference between these quantities (87 MGs) represents the quantity of biodiesel produced from the extracted corn oil obtained from producing 3.41 billion gallons (BGs) of ethanol in 2004. Hence, the total biodiesel production in the new database is about 115 MGs, which is 87 MGs larger than its corresponding value in the traditional database. As mentioned before, we observe this difference because, in this work, we assumed the entire US ethanol industry will follow the new technology, which extracts corn oil from DDGS.

Experiments
To show the implications of extracting corn oil through ethanol production for global land use and greenhouse gas emissions we conducted six experiments of two types. First we do four experiments treating the corn ethanol and soy biodiesel shocks independently. This is the approach used by California and US regulators in establishing induced land use change emission levels. What we vary in these experiments is the treatment of corn oil — how the credit is allocated. The base case for this group is the same simulation with no corn oil. Then we shock corn ethanol and soybean biodiesel together with and without corn oil to get the impact of the combined RFS shocks. This set of experiments provides a broader impact of the total policy. The following is the total set of experiments.

- **Experiment I.** An expansion in corn ethanol from its 2004 level to 15 BGs using the conventional ethanol production technology with no corn oil. Given that the 2004 ethanol production level was 3.41 BGs, the expansion is 11.59 BGs.
- **Experiment II.** An expansion in corn ethanol from its 2004 level to 15 billion gallons using the new ethanol production technology with corn oil extraction.
- **Experiment III.** An expansion in soybean biodiesel from its 2004 level (28 million gallons (MGs)) to 1 BGs using the traditional GTAP model with no

<table>
<thead>
<tr>
<th>Biofuels</th>
<th>Model with no corn oil</th>
<th>Model with corn oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn ethanol</td>
<td>3410</td>
<td>3410</td>
</tr>
<tr>
<td>Sorghum ethanol</td>
<td>0.5</td>
<td>0.514</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>28</td>
<td>115</td>
</tr>
<tr>
<td>Soybean biodiesel</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Palm oil biodiesel</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Rapeseed biodiesel</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Other biodiesel (including corn oil)</td>
<td>2.8</td>
<td>90</td>
</tr>
</tbody>
</table>
corn oil starting from the results obtained from Experiment I with no corn oil. The expansion is 972 MGs.

- **Experiment IV.** An expansion in soybean biodiesel by 598 MGs using the new GTAP model with corn oil starting from the results obtained from Experiment II. This is the amount of soy-based biodiesel that would be needed given the availability of corn oil based biodiesel. This figure is equal to: 1 BGs mandated biodiesel − [available soy and corn oil biodiesel in the base data (115 MGs.) + biodiesel produced using corn oil (287 MGs)] = 598 MGs.

- **Experiment V.** Simultaneous expansions in corn ethanol and soy biodiesel to reach 15 billion gallons of ethanol and 1 billion gallons of biodiesel with no corn oil.

- **Experiment VI.** Simultaneous expansions in corn ethanol and soy biodiesel to reach 15 billion gallons of ethanol and 1 billion gallons of biodiesel including biodiesel produced from corn oil.

The first experiment will be used to measure induced land use emissions per unit of energy produced using the traditional ethanol production process with no corn oil. The second experiment measures induced land use emissions per unit of energy produced through ethanol production plus the corn oil based biodiesel. The third experiment measures the land use emissions per unit of produced energy due to expansion in biodiesel from its 2004 level to 1 billion gallons (the mandated level of biodiesel) in the absence of the extracted corn oil. The results of experiment IV estimate the induced land use emissions to achieve the 1 billion gallon biodiesel mandate in the presence of the extracted corn oil using the new ethanol process.

The results of experiment V show the induced land use emissions for joint expansion in corn ethanol and soybean biodiesel reach 15 billion gallons of ethanol and 1 billion gallons of biodiesel when ethanol producers do not extract corn oil from DDGS. Finally, the last experiment replicates experiment V when ethanol producers extract corn oil from DDGS.

### Simulation results

- **Land use changes**

The induced land use changes obtained from experiments I to V are presented in Table 2 for some selected regions. The first two panels of this table indicate that both models (without and with corn oil) generate similar demands with identical geographical distribution for new cropland to expand corn ethanol to 15 BGs. At the global scale about 1,175 million hectares of new cropland are needed to activate the corn ethanol target. Only a small portion of the demand for new cropland (about 13%) falls in the US, and the rest goes to other regions.

In addition to the expansion in cropland, the increase in corn ethanol causes a conversion of cropland pasture to crop production in the US and Brazil. Both models project similar cropland conversions in Brazil (242,000 hectares) with a tiny difference in US (1,701,000 hectares from the old model versus 1,698,000 hectares from the new model in the US). This difference is because the new model replaces a portion of the produced corn oil with the existing other

### Table 2. Estimated induced land use changes (figures are in 1000 hectares).

<table>
<thead>
<tr>
<th>Description</th>
<th>US</th>
<th>EU</th>
<th>Brazil</th>
<th>Others</th>
<th>Total</th>
</tr>
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<tbody>
<tr>
<td><strong>Experiment I:</strong> corn ethanol with no corn oil</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Crop</td>
<td>153</td>
<td>34</td>
<td>122</td>
<td>866</td>
<td>1,175</td>
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<tr>
<td>Cropland pasture to crops</td>
<td>1,701</td>
<td>0</td>
<td>242</td>
<td>0</td>
<td>1,943</td>
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<tr>
<td><strong>Experiment II:</strong> corn ethanol with corn oil</td>
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<td></td>
</tr>
<tr>
<td>Crop</td>
<td>153</td>
<td>34</td>
<td>122</td>
<td>866</td>
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<td>Cropland pasture</td>
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<td><strong>Experiment III:</strong> Soy biodiesel with no corn oil</td>
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<tr>
<td>Crop</td>
<td>23</td>
<td>4</td>
<td>15</td>
<td>105</td>
<td>148</td>
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<tr>
<td>Converted cropland pasture</td>
<td>306</td>
<td>0</td>
<td>34</td>
<td>0</td>
<td>340</td>
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<td><strong>Experiment IV:</strong> Soy biodiesel with corn oil</td>
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<tr>
<td>Crop</td>
<td>12</td>
<td>2</td>
<td>8</td>
<td>57</td>
<td>78</td>
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<tr>
<td>Converted cropland pasture</td>
<td>154</td>
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<td>18</td>
<td>0</td>
<td>172</td>
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<td><strong>Experiment V:</strong> Simultaneous corn ethanol &amp; soy biodiesel with no corn oil</td>
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<tr>
<td>Crop</td>
<td>178</td>
<td>38</td>
<td>138</td>
<td>928</td>
<td>1,336</td>
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<td>Converted cropland pasture</td>
<td>−2,019</td>
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<td>−276</td>
<td>0</td>
<td>−2,298</td>
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<tr>
<td><strong>Experiment VI:</strong> Simultaneous corn ethanol, corn oil, and soy biodiesel</td>
<td></td>
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</tr>
<tr>
<td>Crop</td>
<td>165</td>
<td>36</td>
<td>130</td>
<td>928</td>
<td>1,260</td>
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<tr>
<td>Converted cropland pasture</td>
<td>−1,860</td>
<td>0</td>
<td>−261</td>
<td>0</td>
<td>−2,122</td>
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</table>
oils used in the base data, and that relaxes the pressure on demand for other oilseeds. This leads to a lower rate of forest conversion in the new model. The share of forest obtained from the model with no corn oil is about 13.3%. The corresponding figure obtained from the model with corn oil is about 12.5%, which is slightly smaller than the result of the first model, but certainly within the error bounds of a CGE model. The geographical distributions of changes in forest, pasture and cropland due to ethanol production obtained from the models with and without corn oil are presented in Figure 3. This figure shows that the models with and without corn oil provide similar geographical distributions for induced land use changes. In general, the induced land use changes due to ethanol production are in line with the results reported in TT.

Figure 3. Induced land use changes obtained from experiments I and II.
While models with and without corn oil project similar land use changes for corn ethanol, they produce different outcomes for soybean biodiesel cases in experiments III and IV. When there is no corn oil produced through ethanol production, we need to increase the US biodiesel from its initial level by 0.972 billion gallons to achieve the mandated level of biodiesel for 2015.

In the third experiment we shock the soybean biodiesel to achieve this goal. On the other hand, in the presence of corn oil produced through ethanol, a portion of the desired expansion in US biodiesel will be produced from corn oil. In this case we only need to increase soybean biodiesel by about 598 MGs to achieve the 1 BGs biodiesel for 2015.

In experiment IV we apply the soybean diesel shock to the database obtained from the second experiment. The biodiesel shock is 598 MGs to reach the 1 BGs biodiesel target when we take into account the amount of biodiesel produced from corn oil. The third and fourth panels of Table 2 summarize the results obtained from experiments III and IV. In the third experiment, global cropland increases by 148,000 hectares to achieve the 1 BG biodiesel target. In the fourth experiment, in the presence of corn oil, global cropland increases by 78 thousand hectares. The areas of cropland pasture converted to crop production in these two cases are about 340,000 hectares and 172,000 hectares, respectively.

The last two panels of Table 2 represent the results for the experiments where we jointly expand corn ethanol and soy biodiesel in the absence and presence of corn oil. In experiment V, the global demand for new cropland (1,336,000 hectares) is slightly higher than the sum of the demands for cropland in experiments I and III (1,323,000 hectares). In this experiment, we get a slightly higher rate of conversion in cropland pasture compared with the sum of experiments I and III (–2,298,000 hectares in experiment V compared with –2,283,000 hectares, which represents the sum of cropland pasture converted in experiments I and III). Finally, in experiment VI when we include corn ethanol in the simultaneous expansion in corn ethanol and biodiesel, the size of global demand for new crop land drops to 1,260,000 hectares (versus 1,336,000 in experiment V). The size of conversion in cropland pasture also falls to 2,122,000 hectares (versus 2,298,000 hectares of the similar experiment with no corn ethanol).

In conclusion, the induced land use changes obtained from the experiments developed in this paper show that including corn oil as a by-product for ethanol production has no major direct implication for induced land changes due to corn ethanol. But it reduces the land requirement for biodiesel production and that helps the US economy to achieve its biofuel targets with lower induced land use changes, as we explain in the next section. We also can conclude that the simultaneous and sequential expansions in biofuels (experiment V versus the sum of experiments II and IV) generate relatively similar results. However, the simultaneous approach generates slightly higher demand for cropland.

### Land use emissions
Traditionally, induced land use emissions have been calculated for each type of biofuel pathway by regulatory organizations, such as the Environmental Protection Agency (EPA) and California Air Resources Board (CARB). The papers published on induced land use emissions follow this tradition. The reason behind this tradition is that so far each biofuel pathway has used its own feedstock independently from other biofuel pathways. But the introduction of the corn oil extraction technology also introduces the question of how should emissions from these joint products be allocated. One can imagine at least the following six options.

- **Assign energy credit from the newly available corn oil to the ethanol industry because it generates the corn oil.**
- **Allocate the credit to the biodiesel industry and argue that with no biodiesel mandate the ethanol industry had limited incentive to extract corn oil from DDGS. In that case, the credit would be given to the biodiesel industry.**
- **Both corn ethanol and soy biodiesel industries share the credit according to their respective shares in incremental energy produced.**
- **The corn oil to biodiesel pathway gets the “credit” and is charged no land use emissions. This is the alternative provisionally chosen by CARB.**
- **Calculate induced land emissions per unit of energy obtained from the simultaneous expansions in corn ethanol and soy biodiesel with no corn oil.**
- **Calculate induced land emissions per unit of energy obtained from the simultaneous expansions in corn ethanol, corn oil, and soy biodiesel.**

In what follows, we define seven cases based on these options to calculate induced land use emissions for corn ethanol and soybean biodiesel in the presence of the new technology that extracts corn oil from DDGS. In addition, we add a case to represent the land use emissions obtained from the old model with no corn oil. In all of these cases we calculate emissions using the CARB
emissions factors. Hence, for the emissions we have the following seven cases:

- **Case A**: No corn oil produced,
- **Case B**: Credit ethanol industry for produced corn oil,
- **Case C**: Credit soy biodiesel industry for produced corn oil,
- **Case D**: Allocate the credit between both corn ethanol and soybean biodiesel based on the incremental energy produced,
- **Case E**: The credit is allocated to the corn oil to biodiesel pathway, to which is charged no land use emissions.
- **Case F**: Divide total emissions from the simultaneous expansions by total energy produced by corn ethanol and soy biodiesel with no corn oil.
- **Case G**: Divide total emissions from the simultaneous expansions by total energy produced by corn ethanol, corn biodiesel and soy biodiesel.

Table 3 represents the induced land use emissions for these cases. **Case A** indicates that with no corn oil the magnitudes of the induced land use emissions for corn ethanol (obtained from experiment I) and soybean biodiesel (obtained from experiment III) are about 14.1 gCO₂/MJ and 16.7 gCO₂/MJ. These figures are larger than their corresponding values obtained from the model with corn oil for cases B, C, D, and E.

Now consider the results obtained for cases **B**, **C**, **D**, and **E**, which are obtained from the model with corn oil. For these four cases we first calculated the total induced land use emissions for corn ethanol and soybean biodiesel using the results of experiments II and IV, respectively. Then in **Case B** the total land use emissions for ethanol are divided by the energy content of ethanol plus corn biodiesel produced in conjunction with ethanol to calculate emissions in terms of gCO₂/MJ. In this case, the total emissions obtained for soybean biodiesel are just divided by the energy content of produced soybean biodiesel. In this case, the magnitudes of the induced land use emissions for corn ethanol and soybean biodiesel are about 13.4 gCO₂/MJ and 14.7 gCO₂/MJ, which are smaller than the corresponding figures reported for **Case A**. The corn ethanol emissions fall because of the corn oil credit, and the soy biodiesel emissions fall because less soy biodiesel is needed to reach the billion gallon RFS level, and that reduces the marginal land requirement for biodiesel production. In addition, using corn oil reduces the share of forest in land conversion slightly in some regions relative to **Case A**.

In the next case, **Case C** we allocated the energy content of the corn oil biodiesel produced in conjunction with ethanol to the soybean biodiesel industry. In this case, the induced land use emissions for corn ethanol slightly decrease (compared with **Case A**) to 13.9 gCO₂/MJ. This figure is slightly lower than the corresponding figure in **Case A** because the new model replaces a portion of the produced corn oil with the existing other oils used in the base data, and that relaxes the pressure on demand for other oilseeds. This leads to a lower rate of forest conversion in the new model and also a lower rate of converting cropland pasture to crop production. In **Case C** the induced land use emissions for soybean biodiesel sharply drops to 9.8 gCO₂/MJ. This is because the corn oil biodiesel produced in conjunction with corn ethanol is large compared with the produced soybean biodiesel.

In **Case D**, we divide the energy content of the corn oil biodiesel between soybean biodiesel and corn ethanol proportional to their share in total incremental energy produced in experiments II and IV. The results of this case are very similar to the results of **Case A**, mainly because the share of ethanol in total energy produced is much larger than the energy produced by the soybean biodiesel industry.

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*The induced land use emissions are calculated using the CARB emissions factors [16].

**These figures represent emissions per unit of energy produced from produced ethanol and biodiesel.
In case E, corn oil biodiesel is considered to be a completely separate pathway. We follow CARB [35] in this case and assume that corn oil biodiesel has zero land use change emissions and allocate none of that credit to corn ethanol or soy biodiesel. However, the fact that corn oil biodiesel exists lowers the demand for soy biodiesel given the assumed RFS total of one billion gallons, so the soy biodiesel emission level remains at the same level as case B. Similarly, the corn ethanol emission level becomes the same as case C. Notice that here we simulated a biodiesel RFS total of 1 billion gallons, but the same kind of effect would have held if we had simulated the new 1.28 billion gallon biodiesel RFS level.

In case F, we get 14.5 gCO₂ per MJ of energy produced from simultaneous expansions in corn ethanol and soy biodiesel when no corn oil is produced. This is very close to a weighted average of ethanol and soy biodiesel emissions in case A. Finally, in the presence of corn oil the simultaneous expansion in ethanol and biodiesel generates 13.5 gCO₂ per MJ of energy produced.

Conclusions
The results obtained from these simulations indicate that extracting corn oil reduces the induced land use emissions due to total biofuel production, as would be expected. In fact, the introduction of this new technology also introduces a new question on how emissions should be allocated. This is because the feedstock of corn oil biodiesel is a joint product with corn ethanol, and it is also in a sense joint with soy biodiesel, at least from a total systems perspective. Thus, there are several options for allocating emissions. We do not take a position on which option is “best,” but present four alternatives, any of which have a certain logic. The options essentially are: (1) credit the extra energy produced to corn ethanol since corn oil is a joint product of corn ethanol, (2) credit the corn oil biodiesel to soy biodiesel since biodiesel is the mandated product, (3) share the corn oil credit between corn ethanol and soy biodiesel proportional to the incremental energy of each product, and (4) assume corn oil biodiesel is an independent product with its own pathway, such that it has a zero land use emissions charge.

Corn ethanol and soy biodiesel emissions fall a bit in all four cases. For soy biodiesel, the fall is because, with corn oil biodiesel, less soy oil biodiesel is needed to meet the RFS mandate, and thus less marginal land use change is needed. The bottom line is that more biofuel is produced from the same or fewer land resources, so total system land use emissions fall. However, the differences among the cases is relatively small for corn. While all CGE and emission factor models used in this context are uncertain, the current state of application of the low carbon fuel standard requires a single number.

In addition, the separation of corn oil extends marketability of DDGS and its uses in the feed ration of wider types of animal species, particularly pork and poultry. The modified DDGS is an effective animal feed with a value similar to previous DDGS, and corn oil can be used for energy or food/feed applications.

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Papers of special note have been highlighted as:

- * of interest
- ** of considerable interest

35 California Air Resources Board. Production of biodiesel from corn oil extraction at dry mill corn ethanol plants (2011).