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## A comparison between GTAP-BIO and GLOBIOM for estimating biofuels induced land use change emissions

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### **Abstract:**

*In this study, we compare two of the most important models in the literature of estimating biofuels induced land use change (ILUC) emissions, GTAP-BIO and GLOBIOM. Since GTAP-BIO is publicly accessible while GLOBIOM currently is not, we use biofuel pathways from the results documented in the most recent GLOBIOM report and compare them using GTAP-BIO with the same specifications. Five EU biofuel pathways, including sugar beet ethanol, starchy crop ethanol, rapeseed oil biodiesel, soy oil biodiesel, and palm oil biodiesel, are tested. The results from GTAP-BIO show lower ILUC emissions for each of the five pathways. The gap in ILUC emission values between the two models is larger for vegetable oil biodiesel pathways than for sugar and starch ethanol pathways. Simulation results are compared to the extent GLOBIOM results were available in the documentation. The major drivers of differences in the two models are livestock rebound response, palm related issues (e.g., palm oil yield and peat oxidation factor), and foregone sequestration on abandoned land. The analysis shows that the strong livestock rebound effect, low palm oil yield, and high abandoned land foregone sequestration factor may lead to an overestimation of ILUC emissions in GLOBIOM.*

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# A comparison between GTAP-BIO and GLOBIOM for estimating biofuels induced land use change emissions

## 1. Introduction

Biofuels have been promoted as an alternative to petroleum-based fuels to mitigate emissions in the transport sector. Conventional biofuels are produced from land-based crops. Promoting conventional biofuels may encourage cropland expansion and cause emissions from land use change. As a result of land competition between croplands and natural lands, interactions among markets, and trade among regions, land use change and related emissions become a global problem that goes beyond the regions expanding biofuels production. This is called biofuels induced land use change (ILUC) emissions. With this concern, several policy bodies (e.g., CARB and US EPA) have included ILUC emissions in measuring the life-cycle emissions from producing biofuels. Thus, ILUC emissions can be a key factor determining the emission feasibility of a biofuel pathway compared with petroleum-based fuels.

Biofuels ILUC emissions have been widely studied in the literature (Ahlgren and Di Lucia, 2014; Broch et al., 2013; Warner et al., 2014; Wicke et al., 2012). However, there are important disparities among models in the baseline assumptions, shock size, simulation approach, and the data used in calculating emissions. Estimating ILUC emissions is subject to notable uncertainty, and uncertainties in economic models can be amplified through the uncertainties in the carbon accounting model (Plevin et al., 2015). For these reasons, estimations across studies are not directly comparable, and there is not a consensus in results from the literature (Woltjer et al., 2017).

In the current study, we compare two of the most important models in the literature, GTAP-BIO and GLOBIOM, in a consistent manner to understand the similarities and differences between the two models. GTAP-BIO and GLOBIOM are two economic models that have been extensively employed in estimating biofuels induced land use change (ILUC) and related emissions. They belong to two different branches of economic modeling. GTAP-BIO is a computable general equilibrium model developed at

the Center for Global Trade Analysis Project (GTAP) at Purdue University. GLOBIOM is a partial equilibrium mathematical programming (constrained optimization) model developed at the International Institute for Applied Systems Analysis (IIASA). GTAP-BIO runs with its coupled emission factor model, AEZ-EF created for the California Air Resource Board (CARB), while the emissions factor model is embedded in GLOBIOM. GTAP-BIO has been used mainly for evaluating biofuels policies in the U.S. and GLOBIOM has concentrated on EU policies. The existing estimations suggest that emission results from the two models can be quite different. In its most recent study (Valin et al., 2015), GLOBIOM reported the ILUC emissions for ten conventional biofuel pathways resulting from the existing EU biofuel policy (see Figure 2 in GLOBIOM report). Compared with ILUC emission values reported in the literature (Ahlgren and Di Lucia, 2014; Warner et al., 2014), GLOBIOM results are mostly at the high end, particularly for vegetable oil based pathways.

GTAP-BIO is publicly accessible while GLOBIOM currently is not. Since we do not have access to the GLOBIOM model, analysis on GLOBIOM in this study is based on information provided in the GLOBIOM report (Valin et al., 2015). To make consistent comparisons, we pick biofuel pathways from the results documented in the GLOBIOM report and test them using GTAP-BIO with the same specifications (e.g., shock size and amortization period). Five EU biofuel pathways are selected including sugar beet ethanol, starchy crop ethanol, rapeseed oil biodiesel, soy oil biodiesel, and palm oil biodiesel. These pathways are available in GTAP-BIO, and they appear to be consistent with corresponding pathways in the GLOBIOM report<sup>1</sup>.

The results from GTAP-BIO show lower ILUC emissions compared with GLOBIOM for each of the five pathways (Figure 1 in section 3). The gap in ILUC emission values between the two models is larger for vegetable oil biodiesel pathways than for sugar and starch ethanol pathways. The motivation of this study is to compare

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<sup>1</sup> The EU starchy crop ethanol pathway was selected since the current version did not split EU starchy crop ethanol production by feedstock. There may be differences in feedstock mix as the base year and data can be different. The inspection indicates that the differences will likely not lead to significant disparity in results.

results from GTAP-BIO and GLOBIOM rigorously to understand the main drivers of the differences in ILUC emissions.

The rest of the paper is organized as follows. Section 2 reviews GTAP-BIO and GLOBIOM to provide a descriptive comparison of the modeling framework and the emission model coverage. In Section 3, the results of the tests of the five pathways from GTAP-BIO are reported and compared with the corresponding GLOBIOM results. Based on the comparisons, several key major areas are identified for in-depth investigation. Section 4 investigates and discusses the major drivers of the differences. Section 5 concludes the study and provides future study recommendations.

## 2. GTAP-BIO and GLOBIOM

GTAP-BIO is a multi-sector multi-region CGE model, based primarily on the standard GTAP database which is the database used by existing well-known CGE models worldwide. The GTAP-BIO model represents: production functions for goods and services; derived demand equations for intermediate and primary inputs (including land by AEZ, labor, capital, and resources); equations to represent households and government demands for goods and services; and equations to model bilateral trade among each pair of countries. Market clearing conditions maintain all markets in equilibrium. These equations endogenously determine supply and demand quantities for all goods and services. The parameters of this model which govern land allocation were tuned according to recent observations on land use changes across the world. The latest version of this model (Taheripour et al., 2017) takes into account multiple cropping and conversion of unused cropland to crop production.

GLOBIOM is a partial equilibrium model of agriculture, forestry and bioenergy sectors. The model is built following a bottom-up setting based on grid cell information, providing the biophysical and technical cost information through specific activity models: the vegetation model EPIC for crops, the digestibility model RUMINANT for livestock, and the G4M model for forestry. These models estimate productivity and environmental indicators for different management based on input data on soil and climate, feeding practices and net primary productivity. In GLOBIOM, as in GTAP-BIO, production,

demand and international trade evolve with the endogenous adjustment of prices. Prices are however fixed for the non-land based sectors (energy, industry, services) in GLOBIOM. Market equilibrium is determined through mathematical optimization which allocates land and other resources to maximize the sum of consumer and producer surplus (Valin et al., 2015).

Land cover in GTAP-BIO includes cropland (including cropland pasture and unused cropland), pasture, and (accessible) forest. Cropland pasture is marginal cropland that is used by the livestock industry and can move to crop production. In GLOBIOM, it includes cropland, grassland, forest, and other natural land. Pasture and forest in GTAP matches grassland and forest in GLOBIOM, respectively. Other natural land (including abandoned land) in GLOBIOM is defined as land not classified as cropland, grassland or forest in the initial land cover data (2000). Abandoned land in the is accounted separately in model projections. Difference in land category and their emission stock can be important driver leading to different ILUC emissions. GLOBIOM did not provide the 2010 land data base they reproduced.

GTAP-BIO has a base year of 2011, and the simulation is comparative static. The model is only shocked once with biofuels mandates for a pathway, and the updated database is compared with the base data. On the other hand, GLOBIOM has a base year of 2000. The model was shocked with constraints to 2010 as an updated base year for evaluating EU biofuels policies towards 2020. Two set of shocks are conducted off 2010. The first set shock only includes macroeconomic and other exogenous trend shocks (baseline) while the second shock set also included the biofuels policy shock. The difference between the two updated databases represents the economic equilibrium changes induced by the biofuels policy. There are important differences in data, model structure, and even shocking mechanism. However, both models estimate ILUC emissions, given a shock of biofuels policy, by first estimating global land use change, and ILUC emissions are then calculated based on the land use change results using the emission factor model. In other words, if the two models resulted in similar land use change results and similar emission factors were used, the ILUC emission results would be comparable. Both models account emissions from natural vegetation

carbon (carbon stored in the forest, pasture, etc.), natural vegetation reversion (foregone sequestration), agricultural biomass carbon, soil organic carbon (SOC), and peatland oxidation. In each source, there could be important differences in assumptions, data sources, and accounting boundaries. Table 1 provides a comparison of the emission factor models by emission source.

Table 1. Comparison of the emission factor models by emission source

Carbon source	AEZ-EF (GTAP-BIO)	GLOBIOM	Comparison
Natural vegetation	Carbon in above and below ground living biomass for the forest, pasture, and cropland pasture. For the forest, it also considers dead wood, litter, understory, litter, and harvested wood products (HWP).	Carbon in above and below ground living biomass for the forest, other natural land, and grassland. The other natural land has much higher carbon stock than the grassland. Carbon in dead wood and litter are considered in the forest.	Different data sources and land category definitions are important factors leading to different natural vegetation biomass carbon results. AEZ-EF includes carbon sequestered in HWP and char carbon if land is cleared using fire while these are not included in GLOBIOM
Foregone sequestration & unused land	Foregone sequestration only for the forest. Emissions from unused land is accounted.	Foregone carbon sequestration on abandoned land.	The emission source of “unused/abandoned land & foregone” represents emissions from converting unused cropland and forest forgone sequestration in GTAP-BIO and emissions from abandoned land reversion in GLOBIOM.
Agricultural biomass	Accounts for changes of carbon stored in crops. Calculated based on updated crop yield from GTAP-BIO.	Crop biomass carbon was annualized over the period of crop growth. Crop yields are from the EPIC model.	The formula used for calculating agricultural biomass carbon is similar for both models. The same palm tree sequestration factors are used (48 MT C/ha).
Soil organic carbon (SOC)	Accounts for both CO <sub>2</sub> and N <sub>2</sub> O emissions associated with loss of SOC for all land conversions. 30-year values were used.	Accounts for CO <sub>2</sub> only and all emissions were assumed emitted over first 20 years.	Both models used the IPCC Tier 1 approach, but different parameters might be applied (e.g., reference year, factors for perennial/tree crops, etc.). For either model, the period of SOC accounting is not varying with the amortization period.

Peatland oxidation	Accounts for emissions from the drainage of peatland for palm expansion in Malaysia and Indonesia	The same with GTAP-BIO.	The same emission factor from the drainage of peatland for palm expansion in Malaysia and Indonesia is used (61 Mg CO <sub>2</sub> /ha/year).
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### 3. Results comparison

Five EU biofuel pathways are tested using GTAP-BIO for ILUC emissions including sugar beet ethanol, starchy crop ethanol, rapeseed oil biodiesel, soy oil biodiesel, and palm oil biodiesel. These pathways are selected since they are already available in GTAP-BIO and they match corresponding pathways in the GLOBIOM documentation. Following GLOBIOM, for each pathway, 123 petajoules (PJ) biofuels mandate, representing 1% of projected EU transport fuel consumption in 2020, is implemented and 20-year amortization period is used for calculating emission intensity throughout this report. Figure 1 presents ILUC emission scores from GTAP-BIO and GLOBIOM for the five pathways studied. GTAP-BIO has lower ILUC emissions for all the five pathways compared with GLOBIOM. Both the ILUC emissions and the emission gap are relatively smaller for ethanol pathways than biodiesel pathways. Sugar beet ethanol has the smallest emission difference (5 g CO<sub>2</sub>e per MJ) while palm oil biodiesel has the largest (202 g CO<sub>2</sub>e per MJ).

The rest of this section interprets ILUC emissions and land use change results for the five pathways from the two models. These results are compared to the extent where GLOBIOM data and results were available in the documentation. The total ILUC emissions of each pathway are decomposed at the global scale into major emission sources including carbon in natural vegetation, foregone sequestration & unused land, agricultural biomass, soil organic carbon (SOC), and peatland oxidation. Table 2 presents the ILUC emission decomposition profiles from the two models. The definitions of these emission sources were introduced in Table 1.



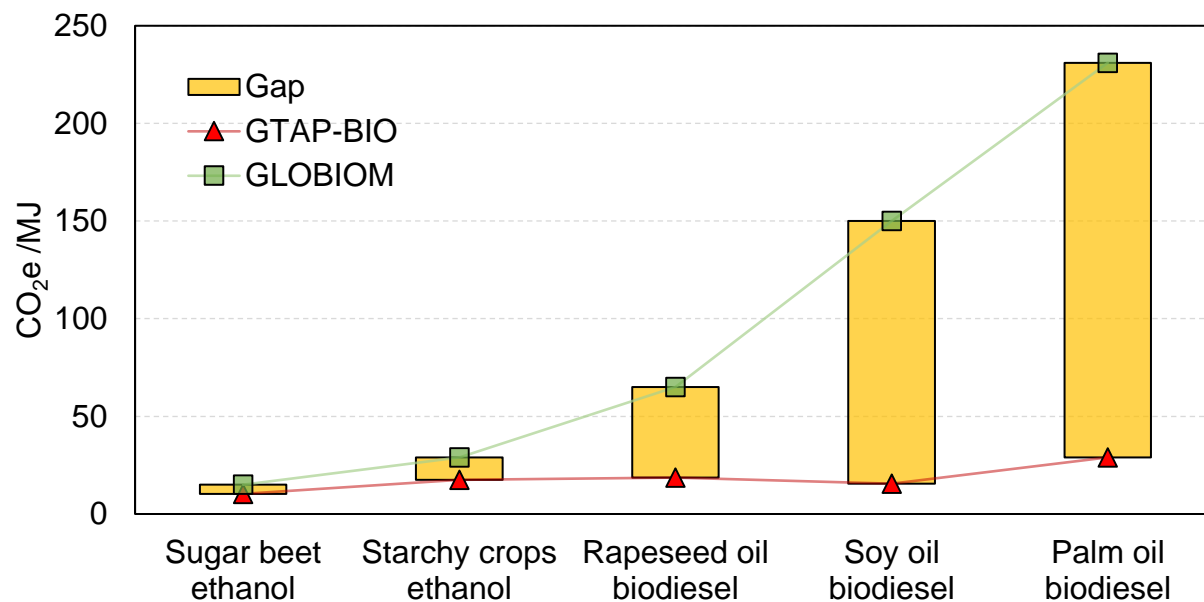


Figure 1. Comparison of ILUC emission scores between GTAP-BIO and GLOBIOM results by biofuel pathway

Table 2. ILUC emission decomposition for the EU biofuel pathways (g CO<sub>2</sub>e per MJ)

Pathway	Model	Natural vegetation	Foregone sequestration & unused land	Agricultural biomass	Soil organic carbon	Peatland oxidation	Total
Sugar beet ethanol	GTAP-BIO	5.5	3.1	-2.6	4.0	0.3	10.3
	GLOBIOM	1.6	4.5	-2.4	10.6	1.2	15.4
Starchy crop ethanol	GTAP-BIO	6.4	3.6	2.1	5.0	0.4	17.5
	GLOBIOM	6.1	10.6	-10.6	20.3	2.8	29.3
Rapeseed oil biodiesel	GTAP-BIO	5.8	3.3	0.7	4.3	4.5	18.7
	GLOBIOM	19.1	14.6	-12.6	29.3	14.6	65.0
Soy oil biodiesel	GTAP-BIO	4.7	1.1	-1.2	5.0	5.9	15.5
	GLOBIOM	99.5	0.0	-24.5	42.8	31.8	149.6
Palm oil biodiesel	GTAP-BIO	15.5	1.6	-17.0	0.9	28.1	29.0
	GLOBIOM	147.2	0.0	-91.1	-7.7	182.9	231.3

### 3.1. Sugar beet ethanol

GTAP-BIO has higher emissions from natural vegetation while GLOBIOM has higher emissions from soil organic carbon. These directly stem from the land use change profiles where GTAP-BIO has relatively more deforestation, and GLOBIOM shows relatively more land conversion from grassland and other natural vegetation. Emissions from avoided natural vegetation regrowth account for 29% of the total emissions in GLOBIOM as a result of EU abandoned land conversion. In GTAP-BIO, 1.2 g CO<sub>2</sub>e per MJ was from foregone sequestration (forest), and 1.9 g CO<sub>2</sub>e per MJ was from converting unused cropland. Sequestrations from agricultural biomass are similar in the two models while GLOBIOM results in higher peatland oxidation.

In both models, EU oilseed area decreased due to sugar beet expansion, which moderately encouraged palm expansion and peat oxidation in South East Asia. The two models disagree on the magnitude of peat oxidation. This may imply important differences in trade modeling framework, vegetable oil substitution, and palm related data.

GLOBIOM reported 55 Mt sugar beet expansion at an average yield of 64 t per ha while the beet expansion yield in GTAP-BIO was much higher (77 t per ha). The yield difference is likely because (1) the crop yields implied in base data are different and (2) the price induced yield responses and yield adjustment per new land quality work differently. GTAP-BIO uses 2011 production and harvested area from FAO. EU Sugar beet yield increased by 0.42% as a result of the ethanol shock in GTAP-BIO while GLOBIOM indicates sugar beet yield decreased. FAO data indicate that EU sugar beet yield has increased by over 40% since 2000.

### 3.2. Starchy crops ethanol

GTAP-BIO shows significantly lower emissions from forgone sequestration, soil organic carbon, and peat oxidation; GLOBIOM has higher sequestration from agricultural biomass. The heterogeneity across emission sources explains the different patterns in land use change whereas GTAP-BIO has more crop switching and cropland

intensification in supplying feedstock production while GLOBIOM shows more cropland expansion into natural vegetation and abandoned land. Sequestration in agricultural biomass complements emissions from natural vegetation and soil organic carbon since agricultural biomass increases at the cost of converting land with high natural vegetation and soil carbon. GTAP-BIO shows agricultural biomass loss as a result of more crop switching (to low carbon crops) as opposed to natural vegetation loss. In GLOBIOM, emissions from avoided natural vegetation regrowth accounts for 36% of the total emissions as a result of extensive EU abandoned land conversion. The data and assumptions used for abandoned land foregone sequestration calculation in GLOBIOM are highly uncertain and subject to further investigations (as discussed in Section 4.3 in detail). In GTAP-BIO, 1.4 g CO<sub>2e</sub> per MJ was from foregone sequestration (forest), and 2.2 g CO<sub>2e</sub> per MJ was from converting unused cropland.

GLOBIOM indicates feedstocks for producing 123 PJ ethanol was distributed across maize (7.9 Mt), wheat (5.2 Mt), and rye (1.9 Mt); these feedstock demands would translate to 2.6 Mha with 2011 EU crop yields or even lower numbers with the higher yields in more recent years. However, GLOBIOM implied additional feedstock expansion of 11.3 Mha, 81% of which was located in EU. It is not clear why GLOBIOM resulted in a feedstock area expansion over three times higher than required. Note that the calculation has not even accounted for the displacement from coproducts, which, if considered, would further decrease the feedstock expansion as demonstrated in GTAP-BIO. In GTAP-BIO, additional feedstock (wheat and other coarse grain) production increased by 5.5 Mt with 0.8 Mha global area expansion.

There are many reasons that are potentially causing the higher feedstock demand in GLOBIOM relative to GTAP-BIO, for example, lower crop yields and weaker yield responses, lower substitution in consumption, and limited crop switching. Nonetheless, the critical driver for the excessive cereals expansion appears to be the livestock rebound effect in GLOBIOM. In GLOBIOM, the coproducts from the ethanol production (DDGS) are used as protein feedstuff in livestock sectors. Due to the rigid feed rations, more cereals are produced to complement the protein coproducts to supply livestock sectors. As a result, livestock sectors expand in GLOBIOM, and it

showed a global production increases in meat (+100 kt) and milk (+290 kt). The livestock rebound effect was not seen in GTAP-BIO as the livestock sectors shrunk globally by 0.01% (in EU, production in meat decreased by -0.05% and in dairy dropped by -0.02%). In GTAP-BIO, the livestock production declined due to the higher feed prices driven by factors (e.g., land, capital) reallocation from livestock sectors to sectors promoting biofuels production. In addition, GLOBIOM also demonstrated a strong displacement between the coproducts from the ethanol production and protein meals for cattle. The decrease in protein meal demand leads to substitutions from high meal rate oilseeds (e.g., soybeans) to low meal rate oilseeds. This encourages the oil palm expansion on peatland in Malaysia and Indonesia, which explains the high peat oxidation from GLOBIOM.

### 3.3. Rapeseed oil biodiesel

GTAP-BIO results in the total emissions from natural vegetation, agricultural biomass, and soil organic carbon compared with GLOBIOM (11 vs. 36 g CO<sub>2e</sub> per MJ), mainly because of the higher cropland expansion into the forest and other natural vegetation. GLOBIOM emissions from foregone sequestration & unused land and peatland oxidation are more than tripled GTAP-BIO results, implying high conversion of abandoned land and stronger palm expansion on peatland. In GLOBIOM, 23% of the total emissions are from avoided abandoned cropland regrowth. In GTAP-BIO, 1.0 g CO<sub>2e</sub> per MJ was from foregone sequestration (forest), and 2.4 g CO<sub>2e</sub> per MJ was from converting unused cropland.

The 123 PJ biodiesel shock entails 3.5 Mt of rapeseed oil as feedstock input. About 8 Mt of rapeseed is needed to meet the oil demand for biodiesel production. Due to market-mediated effects on the demand margin, for both rapeseed and rapeseed oil, other consumption would decrease, and substitutions would increase, as a response to higher prices. Thus, less than 8 Mt rapeseeds would be newly produced from the models. In GLOBIOM, the global rapeseed production increased by 6.2 Mt with 1.9 Mha rapeseed area expansion. In GTAP-BIO, rapeseed production rose by 2.7 Mt with 1.0 Mha area expansion. This implies that GTAP-BIO has significantly stronger market-

mediated effects where demand margins (consumption reduction and substitution of rapeseed and rapeseed oil) played a more important role. Potential key drivers of the different magnitude of the demand margin responses could be differences in the modeling framework of vegetable oil substitution and international trade between the two models. It requires more detailed data and results from GLOBIOM in both oilseed markets and vegetable oil markets for further analysis.

It is important to note that, in GLOBIOM, the total rapeseed area expansion is equal to the cropland expansion (1.9 Mha). Several possible reasons for the high cropland expansion relative to rapeseed expansion could be: (1) GLOBIOM allows little crop switching as a way supplying rapeseed production (in GTAP-BIO, other crops decreased by 749 kha globally). (2) No cropland intensification in GLOBIOM, which may lead to the high pressure on the extensive margin. (3) Strong livestock rebound effect in GLOBIOM induced by the increased rapeseed meal supply encouraged grain expansion (+ 1.1 Mt). As a result, livestock sectors benefited from the biodiesel shock and meat and milk production expanded globally by 130 kt and 330 kt, respectively. On the other hand, in GTAP-BIO, the livestock sectors shrunk globally by 0.002% in meat and 0.004% in dairy, and cereal grains and other feed crops were a major source of land for conversion. The two models obviously disagree on how proteins substitute other feedstuffs in the livestock sectors. The livestock rebound effect in GLOBIOM plays a critical role in affecting ILUC emissions. This issue is further discussed in section 4.1.

Both models showed peat oxidation as an important part of the ILUC emissions. The GLOBIOM value is triple the GTAP-BIO value. In GTAP-BIO, palm fruit production increased by 0.8 Mt globally with 38 kha new palm area (73% in Malaysia and Indonesia). About 30% of the palm expansion in Malaysia and Indonesia was on peatland (8.3 kha). In GLOBIOM, oil palm plantation increased by 110 kha in Southeast Asia. One-third of the palm expansion in Malaysia and Indonesia was assumed to be grown on peatland. The same peat oxidation factor was applied in the two models, so the high palm area expansion directly explains the high peatland oxidation in GLOBIOM.

### 3.4. Soy oil biodiesel

Compared with the rapeseed oil biodiesel case, several differences with the soy oil biodiesel case could be: (1) Crop yields are different between soybeans and rapeseed. (2) Soybean has higher meal rate than rapeseed (80% vs. 56%). (3) Much of the soybeans or soybean oil would be imported to EU since soybean has a relatively weaker comparative advantage compared with rapeseed in the EU (much of the rapeseed was produced in EU in the rapeseed oil biodiesel case). In GTAP-BIO, the emission decomposition profile for the soy case appears to be similar to the rapeseed case since these differences did not matter much across the two cases. However, this is not the case in GLOBIOM. For some unclear reasons, no abandoned land was converted in GLOBIOM for the soy case so that there were no emissions from foregone sequestration & unused land. Relatively more land had to be converted from forest and other natural vegetation, leading to high emissions from natural vegetation and soil organic carbon. The peatland oxidation in GLOBIOM was considerably higher than GTAP-BIO results, implying stronger vegetable oil substitution from palm oil. With the stronger palm expansion, sequestrations in palm tree as a part of agricultural biomass also increased.

The 123 PJ biodiesel shock entails 3.5 Mt of soy oil as feedstock input, which requires 18 Mt of soybeans for production. In GLOBIOM, the global soybeans production increased by 7.3 Mt with 1.8 Mha soybeans area expansion. In GTAP-BIO, soybean production increased by 3.5 Mt with 1.0 Mha area expansion. This implies that GTAP-BIO has stronger market-mediated effects through demand margins (increase in substitutions and decrease in consumption).

In GLOBIOM, the total soybeans area expansion (1.8 Mha) is smaller than the total cropland expansion (2.0 Mha). Similar potential reasons have been discussed in the rapeseed oil biodiesel in section 3.3. However, compared with the rapeseed case, in GLOBIOM, the soy case demonstrated much stronger livestock rebound effect (production in livestock sectors is three times higher) because of the higher meal rate in soybean relative to in rapeseed. The livestock rebound effect also encouraged grain

expansion, and the production of meat (620 kt) and milk (1280 kt) increased globally in GLOBIOM. In GTAP-BIO, production from livestock sectors remained roughly unchanged from the global perspective. However, because of the high meal rate in soybeans relative to rapeseed, livestock sectors expanded moderately compared with the rapeseed case.

In GTAP-BIO, palm fruit production increased by 1.2 Mt globally with 55 kha new palm area (74% in Malaysia and Indonesia). About 26% of the palm expansion in Malaysia and Indonesia was on peatland (11 kha). In GLOBIOM, oil palm plantation increased by 240 kha in Southeast Asia. However, besides oil palm expansion, cereal production also increased in Southeast Asia. Consequently, cropland increased by 560 kha in increased in the region, converted from grassland (160 kha), primary forest (150 kha), and other natural vegetation (260 ha). Converting tropical forest and other natural vegetation often accompanied by extremely high emissions from natural vegetation and soil organic carbon, which partly interprets the difference in emission decomposition profiles. In addition, many factors may lead to high palm expansion (e.g., disparities in palm fruit yield and yield responses, oil extraction efficiency, and coproducts modeling). The test for palm oil biodiesel (section 3.5) unveils these issues in depth.

### 3.5. Palm oil biodiesel

GLOBIOM presents considerably higher emissions compared with GTAP-BIO, but both models agreed that (1) natural vegetation and peatland oxidation are two major sources of emissions mainly due to the deforestation in Southeast Asia and (2) agricultural biomass represents a strong carbon sink mainly due to the high sequestration in palm trees. The extremely higher peatland oxidation in GLOBIOM implies higher palm expansion in Southeast Asia compared with GTAP-BIO. It is unsure why GLOBIOM showed negative soil organic carbon emissions. Palm tree as a perennial crop would lead to soil organic carbon sequestration if growing on annual cropland. It is likely that GLOBIOM had more soil organic carbon sequestration from palm expansion than soil organic carbon loss from other conversions. Similar to the soy oil biodiesel case, no abandoned land was converted in GLOBIOM for the palm case so that there were no emissions from foregone sequestration & unused land.

The 123 PJ biodiesel shock entails 3.5 Mt of palm oil as feedstock input, which requires 14 Mt of palm fruit for production. In GLOBIOM, the palm oil production increased by 3.1 Mt with 1.2 Mha palm area expansion in Southeast Asia. In GTAP-BIO, the global palm fruit production increased by 5.3 Mt with 259 kha palm area expansion. This also implies the stronger market-mediated effects through demand margins in GTAP-BIO, for example, the palm oil shock also led to global expansion in other vegetable oils for substitution (about 1.2 Mt production increase in rapeseed and other non-soybean oilseeds).

The implied palm oil yield from GLOBIOM is 2.6 t per ha in Southeast Asia, which is significantly lower than the 2011 yield (4.5 t per ha, including palm kernel oil) for Malaysia and Indonesia from FAO. Many factors are affecting the palm oil yield (e.g., oil extracting efficiency, immature palm area, and palm kernel oil coproducts). The investigations in Section 4.2 indicates that the palm oil yield used in GLOBIOM was understated and it played an important role in determining ILUC emissions, particularly for vegetable oil biodiesel pathways.

About 27% of the palm expansion in Malaysia and Indonesia was on peatland (51 kha) in GTAP-BIO which is much smaller than the converted peat area in GLOBIOM (one-third of palm expansion in Malaysia and Indonesia) given the extensively larger palm expansion. In addition, in GLOBIOM, 96% of palm area expansion was from Southeast Asia while the number is 78% in GTAP-BIO. Central and South America and Sub-Saharan Africa are also important palm oil suppliers in GTAP-BIO, and no peatland oxidation was accounted for palm expansion in these regions. This may partly explain the high peat oxidation in GLOBIOM as well. Given the importance, the peat oxidation factor, as well as the share of palm expansion on peatland, are discussed in depth in section 4.2.

#### 4. Discussion of major issues

In this section, we investigate and discuss the most important drivers of the difference in the ILUC emissions from the two models. These drivers include livestock



rebound response, palm related issues, and foregone sequestration on abandoned land.

#### 4.1. Livestock rebound effect

When shocking a pathway generating protein feedstuff coproduct, on the one hand, one may expect that biofuels feedstock expansion would lead to higher crop feedstuff prices and pasture rent due to the factor competitions, which in turn diminishes livestock production. On the other hand, the coproduced protein feedstuff enters livestock industries at a lower price, which benefits livestock sectors. Due to the feed ration requirements, cereal grains (energy feedstuff) are demanded to complement the excessive proteins to supply livestock sectors. In other words, the dispersion of the protein feedstuff leads to (1) growth in livestock production and (2) expansion in cereal grains area and production to satisfy the additional demand from the livestock sectors. This is called the livestock rebound effect. In the three protein feedstuff generating pathways tested (starchy crops ethanol, rapeseed oil biodiesel, and soybean oil biodiesel), GLOBIOM showed strong livestock rebound effects while GTAP-BIO had mostly contraction in livestock production. It appears that the magnitude of the livestock rebound effect in GLOBIOM was closely related to the protein content in the biofuels coproducts. Higher protein feedstuff rate in feedstock encourages stronger livestock rebound effect, which in turn leads to higher ILUC emissions.

To understand the importance of the livestock rebound effect in affecting ILUC emissions, we developed two tests in GTAP-BIO based on the rapeseed oil biodiesel and soy oil biodiesel pathways. Along with the biofuels mandate shocks, livestock sectors are also shocked globally to match GLOBIOM results for the two pathways, respectively. The tests may generate inconsistencies in regional livestock production due to the lack of detailed information from GLOBIOM, but the results represent our best estimation. Figure 2 presents the results for the tests for the case of matching the livestock production in GLOBIOM. GTAP-BIO emissions would grow by 18 g CO<sub>2e</sub> per MJ for the rapeseed oil biodiesel pathway and 72 g CO<sub>2e</sub> per MJ for the soy oil biodiesel pathway. These test results demonstrate that the livestock rebound effect

plays a critical role in explaining the ILUC emission difference between the two models. They also confirm that stronger livestock rebound effect leads to higher ILUC emissions.

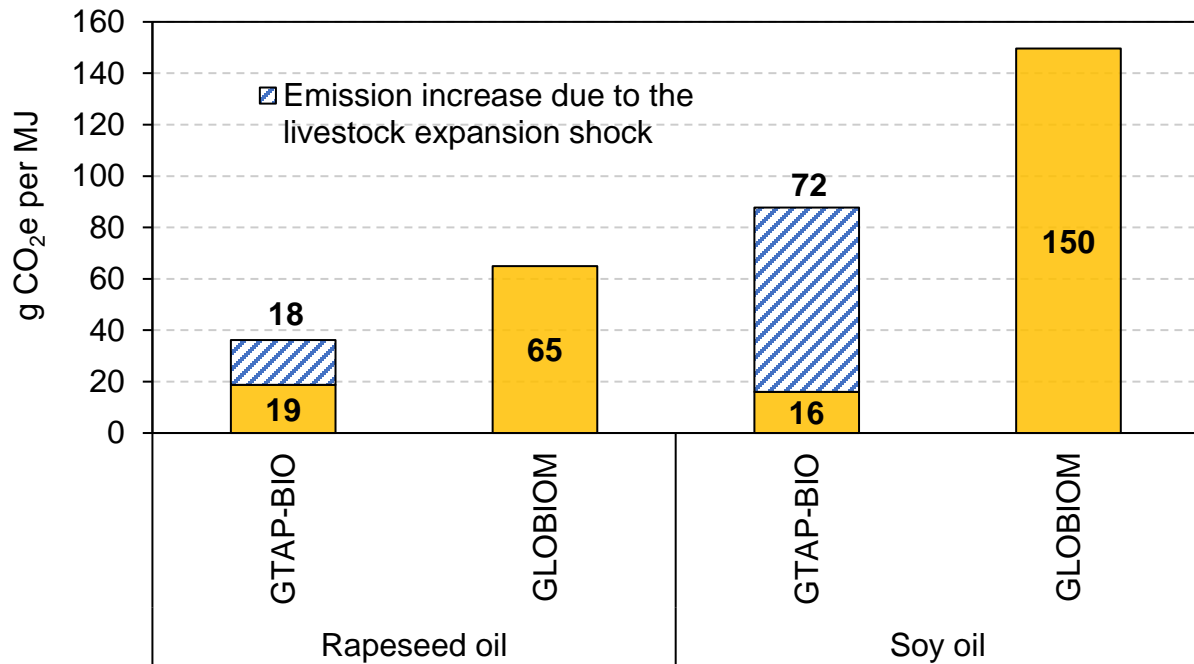


Figure 2. Test results for increasing livestock expansion in GTAP-BIO matching GLOBIOM for rapeseed oil and soy oil biodiesel pathways

No evidence has shown that promoting biofuels led to livestock expansion in the past. On the contrary, the growing demand for protein meals has been the main driver for the global expansion of oilseed production (Alexandratos and Bruinsma, 2012). To investigate the issue, we identified the following drivers leading to the much stronger livestock rebound effect in GLOBIOM compared with GTAP-BIO.

(1) Missing vegetable oil in GLOBIOM

GLOBIOM includes only four vegetable oils (rapeseed oil, soy oil, sunflower oil, and palm oil), accounting for about 83% of the world total vegetable oil production. For vegetable oil biodiesel pathways, missing other vegetable oils may limit vegetable oil substitution in the model. As a result, more new vegetable oil is demanded, and more meals are produced.

## (2) Missing animal feed crops in GLOBIOM

GTAP-BIO includes all the crops in the FAO database while whereas GLOBIOM only represents a subset of them (about 86% in harvested area). Many animal feed crops were not included in GLOBIOM. Missing these crops prevented possible substitution between protein meals and these crops. In particular, some feed crops have high protein content and have been used as protein crops; for example, field peas, broad beans, lupins (over 10 Mha of these three protein crops are being grown in 2015 in the world). Missing these crops limited demand for protein meals and restricted area supplied by crop switching, and as a result, encourages livestock expansion and increases cropland expansion.

## (3) Rigid feedstuff substitution in livestock sectors in GLOBIOM

In GLOBIOM, the substitution in feedstuffs appeared to be very rigid since technologies were model at micro-level. Substitution in GLOBIOM is prohibited under a technology, but switching among technologies (e.g., from low-protein to high-protein) provides a way of increasing protein feedstuff consumption. On the other hand, technologies in GTAP-BIO are modeled at macro-level, which permits more flexible substitution. It is important to note that an important factor that contributed to the increase in protein as feed and the decrease in the use of cereals as feed has been the shift towards more balanced feed rations (Alexandratos and Bruinsma, 2012). This is particularly the case for developing and underdeveloped countries where growth in protein meal consumption significantly exceeds livestock production. Figure 3 presents the growth in protein meal consumption and animal production in 2026 relative to 2016-2016 projected by OECD/FAO (2017). This indicates that at macro-level, there could be substitution between protein meals and other feedstuffs. Furthermore, a portion of soybean and rapeseed produced are used as feedstuff directly (e.g., 22 Mt in the world and 3.9 Mt in Europe whole soybeans were used as feedstuff in 2015 (USB, 2017)). Allowing a flexible feedstuff substitution permits increases in crushing of these oilseeds to reduce new production. This effect also played an important role in GTAP-BIO.

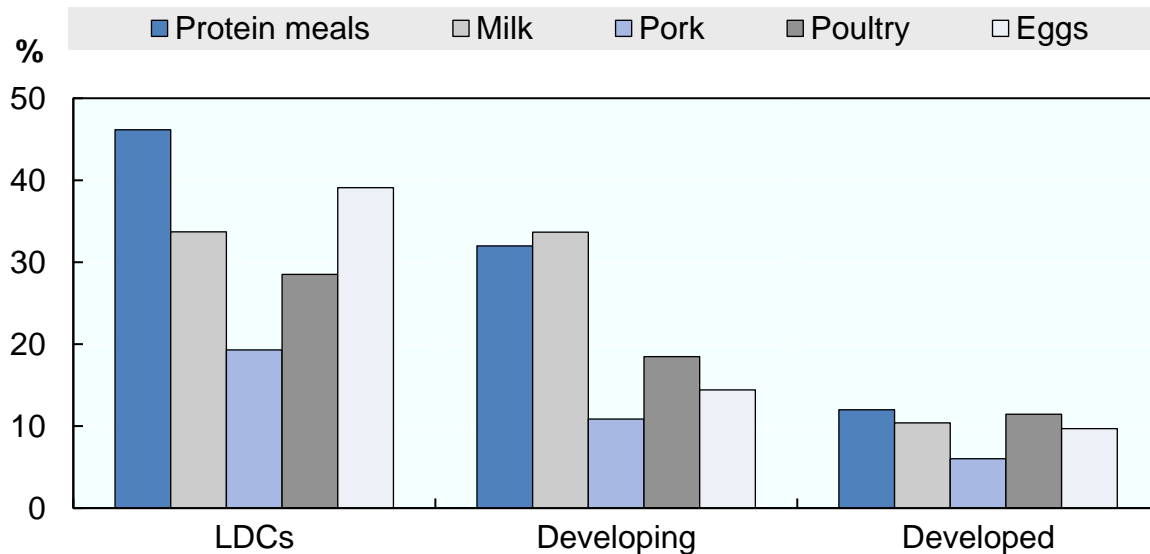


Figure 3. Growth in protein meal consumption and animal production in 2026 relative to 2016-2016. Source: OECD/FAO (2017)

(4) Missing protein meal demands from non-livestock sectors in GLOBIOM.

In GLOBIOM, the only outlet of the protein meal is to enter livestock sectors as feedstuff. However, in GTAP-BIO, besides the major demand from livestock sectors, protein meals also supply other sectors (e.g., processed food). With the lower protein meal prices, the demand from non-livestock sectors would increase as well so that fewer protein meals would enter the livestock sectors.

(5) The baseline assumptions of diet pattern changes and livestock expansion in GLOBIOM.

As mentioned GTAP-BIO runs comparatively static and only shocks biofuels policies. GLOBIOM runs dynamically, and it has considered the increase in meat consumption due to diet pattern changes in the baseline. However, due to the interactions between the livestock production and biofuels expansion, the baseline shock for livestock industries could be important in affecting the livestock rebound effect. It is not clear how the diet pattern changes were implemented in GLOBIOM. However, the baseline should reflect that the growing demand for livestock production would be the main driver for the oilseed and vegetable oil expansion.

## 4.2. Palm related issues

As indicated in the above comparisons, peat oxidation and tropical deforestation may play an important role in ILUC emissions, particularly for vegetable oil biodiesel pathways. Palm expansion was the key reason for those emissions. Thus, in this section, we explore some key palm related drivers to the model differences.

### 4.2.1. Palm kernel oil and palm kernel meal

Palm kernel oil and palm kernel meal are two important coproducts from producing palm oil. About 6 Mt of palm kernel oil and 7 Mt of palm kernel meal were produced in the world in 2011. In GTAP-BIO, palm kernel oil is modeled together with palm oil assuming perfect substitution to represent the coproduction; palm kernel meal enters livestock sectors as feedstuff. In GLOBIOM, these coproducts from producing palm oil were not included. Missing palm kernel oil effectively lowers palm oil yield by over 10%, which in turn increases palm area demand. Missing palm kernel meal may understate its substitution with traditional land-based feedstuff, which also leads to an increase in total land use. Including palm kernel meal may also alleviate the livestock rebound effect in GLOBIOM since kernel meal is used as high fiber and energy feedstuff.

### 4.2.2. Palm oil yield

As discussed in palm oil biodiesel results (section 3.5), the palm oil yield implied in the GLOBIOM results was significantly lower than the yield in GTAP. The consideration of palm kernel oil has been discussed. Several other important factors may contribute to the palm oil yield difference:

#### (1) Palm oil extraction efficiency

As indicated in the GLOBIOM documentation (pg. 212), the crushing rates in 2000 were used and kept constant over time for all oilseeds. However, the oil extraction efficiency has been increasing over time, particularly for palm oil. The palm oil extraction rate increased by 11% from 2000 (19%) to 2011 (21%) in Malaysia and Indonesia

(FAOSTAT, 2017). The oil extraction rate for other oilseeds also increased slightly over time (e.g., US soy oil).

## (2) Plantation area and harvested area in palm fruit yield

GLOBIOM accounts for immature palm area by using the palm plantation area adjusted palm fruit yield (pg. 210 in the GLOBIOM documentation). GTAO-BIO has been using yield from FAO, which uses harvested area. The difference is because oil palm will not have any production in the development period (first 3 years of the 20-30 years life). In a steady state, the harvest ratio (harvested area over plantation area) would be around 90%. Indonesia has a very low harvest ratio of 75% due to the high palm expansion rate while Malaysia (88% harvest ratio) is approaching the steady state. It is reasonable to consider the immature palm area expansion and related emissions caused by the biofuels shock. From a consequential approach perspective, the harvest ratio at the steady should be used. GTAP-BIO is working on including immature palm area in the data and model. However, GLOBIOM is likely using a harvest ratio at the current expanding state, which may lead to an overestimation of immature palm area expansion due to a biofuel shock.

## (3) Crop yield responses

As a response to higher land prices caused by the biofuels shock, palm fruit production would intensify by using relatively less land but relatively more other inputs. This price induced yield response is included in GTAP-BIO endogenously. It is also a way to reflect the historical yield increase in the model. The yield response in the model directly affects the yield in the updated database. The yield increase played a much more important role in supplying palm demand in the GTAP-BIO results compared with GLOBIOM.

### 4.2.3. Palm expansion on peatland

GLOBIOM assumes one-third of palm expansion will be on peatland. The GTAP-BIO results showed this share to be 26%-33% depending on pathways. In both models, the one-third assumption was estimated by Edwards et al. (2010), and it represented

the period with high palm expansion and peat loss. However, this may change in the future given the increasing government and international attention to the issue.

Determining the location of palm expansion is very important in affecting peatland oxidation and tropical deforestation. A recent study from Miettinen et al. (2016) created peatland maps at 30 m resolution for Peninsular Malaysia, Sumatra, and Broneo, which are the major palm production area in Malaysia and Indonesia. The study reported that 20% of the total peatland (15.7 Million ha) in the study area had been disturbed for industrial oil palm plantation. Using this data, we calculate that about 19% of palm expansion was on peatland in the study area. A study from Gunarso et al. (2013) also showed that, in 2010, 22% of the palm oil expansion in Indonesia and 13% of oil palm expansion in Malaysia were on peatland. To understand the potential palm expansion pattern on peatland in the future, we overlaid the peatland map from Miettinen et al. (2016) with the Indonesia palm concession map from Global Forest Watch (GFW, 2017). The results show that for Sumatra and Borneo, Indonesia, there are about 2.4 Mha of palm concession on peatland with tiny pristine peat swamp forest (PSF) and 0.42 Mha of degraded PSF. Over 1 Mha has been used under industrial palm plantations. This indicates that future palm expansion on high-emission peatland may be limited in Indonesia.

#### 4.2.4. Peat oxidation factor

AEZ-EF uses the 95 t CO<sub>2e</sub> /ha/year for peat oxidation estimated by Hooijer et al. (2010). However, in this study, the peat oxidation factor from GLOBIOM, 61 t CO<sub>2e</sub>/ha/year, was used in AEZ-EF for the comparison. The GLOBIOM value was an average value of a literature survey. For both AEZ-EF and GLOBIOM, a uniform value was used for peat oxidation factor, and the value was estimated for pristine peat swamp forest. Nevertheless, as indicated by Miettinen et al. (2017), the factor should be conditional on the quality and current use of the peatland. The studies suggested 55 t CO<sub>2e</sub> /ha/year for pristine peat swap forest, 45.3 t CO<sub>2e</sub> /ha/year for degraded peat swap forest, and 35.6 for tall shrub/secondary forest. Further research is needed for determining palm expansion on peat by type. This evidence indicates that the peat oxidation in ILUC emissions may be overestimated in the two models.

#### 4.3. Abandoned land foregone sequestration in GLOBIOM and emissions from converting unused land in GTAP-BIO

In GLOBIOM, it assumes that there is a trend of cropland being abandoned in EU and Oceania in the baseline. Biofuels expansion would slow the rate of cropland abandoning so that abandoned land would effectively supply cropland. GLOBIOM assumes that the abandoned land, if not brought back to production, would revert to the forest or other natural vegetation. It follows the EPA (EPA, 2010) method in determining the share of reforestation on abandoned land (to be the same with the share of forest or other natural vegetation already observed on fertile land in the same region). Constant carbon stock is used for other natural vegetation reversion. However, for the forest reversion emission factor, the EPA study conservatively applied foregone forest sequestration rate while GLOBIOM assumes a full forest regrowth in 20 years. In other words, converting abandoned land is partly equivalent to cropland expansion into the forest and other natural vegetation. The assumptions may be too strong and entail more careful investigation, for the following reasons:

- (1) The GLOBIOM report disclosed neither the information of the cropland abandoning trend nor how biofuels shocks affect the trend, both of which could be important for EU pathways in GLOBIOM. Cropland is abandoned for reasons. The economic drivers need to be investigated and modeled other than simply assuming a trend in the baseline.
- (2) Abandoned land is usually degraded land with low productivity so that the possibility and speed of natural vegetation reversion on abandoned land are low. The impact of cropland abandonment on the environment is uncertain and controversial, e.g., soil carbon sequestration in some cases (Schierhorn et al., 2013) and desertification and soil erosion in other cases (Benayas et al., 2007).
- (3) Abandoned lands may have other uses (e.g., grazing) or be subject to government policy guidance which may prevent the natural vegetation reversion (Terres et al., 2015).



In a comparative static setup in GTAP-BIO, the trend of regional cropland abandoning will not be captured since the measurement focuses only on biofuels policy as a driver to ILUC emissions. Cropland being abandoned, on the other hand, is not an economic driver being affected by the biofuels policy, but the consequence of other economic drivers that have not been clearly modeled. Studies have shown that institutional and socio-economic factors (e.g., land use policies or social problems such as the collapse of the former Soviet Union) were more important than biophysical conditions in determining land abandonment (Alcantara et al., 2013; Hatna and Bakker, 2011). Given that there has been no clear linkage between biofuels expansion and drivers to cropland abandonment, the response increasing abandoned land supply has not been included in GTAP-BIO.

In GTAP-BIO and AEZ-EF, one of the recent improvements was the inclusion of cropland supply from multi-cropping and unused cropland. In a recent update, emissions from converting unused cropland were included by assuming the same emission factors for converting cropland pasture. Cropland intensification through multi-cropping does not generate ILUC emissions. The emission factors for unused land are still under evaluation. In comparison, the abandoned land in GLOBIOM may map to a mix of unused cropland, cropland pasture, and cropland in GTAP-BIO. In AEZ-EF, the same emission factors are assigned to unused cropland and cropland pasture. These factors are smaller than the emission factors for other natural vegetation in GLOBIOM. However, crop switching generates little or no ILUC emissions. This partly explains the higher ILUC emissions from GLOBIOM compared with GTAP-BIO for pathways using abandoned land. It is unclear why abandoned land is not available for the soybean oil and palm oil biodiesel cases. Both soybean oil and palm oil biodiesel cases in GLOBIOM entailed extensive feedstock import and significantly encouraged palm expansion on peatland. If abandoned land were allowed to be used (cropland supply increases) in these two cases, the high vegetable oil prices induced by the biodiesel shocks might encourage oilseeds (e.g., rapeseed or sunflower) expansion in EU, which might in turn provide substitutions to palm oil and soy oil and alleviate deforestation and peat oxidation in palm expansion regions. For the soy oil biodiesel case, substitution from low-meal-rate vegetable oil also could reduce the livestock rebound effect induced

by soy meal, which would further reduce ILUC emissions. Thus, including abandoned cropland into the economic boundary may have mixed impacts on ILUC emissions when evaluating a biofuel pathway. On the one hand, abandoned cropland if assuming natural vegetation regrowth may lead to higher emissions compared with active cropland; on the other hand, including abandoned cropland encourages cropland supply, which may alleviate deforestation and emissions from carbon hotspots. However, the bottom line is they have to be modeled consistently based on careful investigations and sound evidence.

## 5. Summary of findings

The results from GTAP-BIO show lower ILUC emissions compared with GLOBIOM for each of the five pathways. The gap in ILUC emission values between the two models is larger for vegetable oil biodiesel pathways than for sugar and starch ethanol pathways. The motivation of this study is to compare results from GTAP-BIO and GLOBIOM rigorously to understand the main drivers of the differences in ILUC emissions.

The major drivers of differences in the two models are livestock rebound response, palm related issues (e.g., palm oil yield and peat oxidation factor), and foregone sequestration on abandoned land. The livestock rebound effect is very important in driving emissions in GLOBIOM. Essentially, the added supply of protein feedstuffs induces GLOBIOM to grow more grains to make use of the protein feeds in a larger livestock sector. Essentially, all the emission associated with the growth in the livestock sector get charged to the biofuels.

The palm oil yield and peat oxidation factor are also quite important. Since palm oil substitutes for other vegetable oils, what happens to palm and its emissions is important in all the pathways, but especially, of course, the oilseed pathways. In this analysis, we detail a number of reasons why we believe that the palm oil yield and peat oxidation factors in GLOBIOM do not provide an accurate representation of what seems to be actually happening in the region or in world markets.

Finally, the abandoned land emission factors and use of abandoned in some but not all pathways also are important. We provide data to support that the approach to handling abandoned land and the emission factors assigned to it may not be appropriate in GLOBIOM.

## References

- Ahlgren, S., Di Lucia, L., 2014. Indirect land use changes of biofuel production—a review of modelling efforts and policy developments in the European Union. *Biotechnology for biofuels* 7, 35.
- Alcantara, C., Kuemmerle, T., Baumann, M., Bragina, E.V., Griffiths, P., Hostert, P., Knorn, J., Müller, D., Prishchepov, A.V., Schierhorn, F., 2013. Mapping the extent of abandoned farmland in Central and Eastern Europe using MODIS time series satellite data. *Environmental Research Letters* 8, 035035.
- Alexandratos, N., Bruinsma, J., 2012. *World agriculture towards 2030/2050: the 2012 revision*. ESA Working paper Rome, FAO.
- Benayas, J.R., Martins, A., Nicolau, J.M., Schulz, J.J., 2007. Abandonment of agricultural land: an overview of drivers and consequences. *CAB reviews: Perspectives in agriculture, veterinary science, nutrition and natural resources* 2, 1-14.
- Broch, A., Hoekman, S.K., Unnasch, S., 2013. A review of variability in indirect land use change assessment and modeling in biofuel policy. *Environmental Science & Policy* 29, 147-157.
- Edwards, R., Mulligan, D., Marelli, L., 2010. Indirect land use change from increased biofuels demand. Comparison of models and results for marginal biofuels production from different feedstocks., EC Joint Research Centre, Ispra.
- EPA, 2010. Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis. Technical Report EPA-420-R-10-006. Assessment and Standards Division, Office of Transportation and Air Quality.
- FAOSTAT, 2017.
- GFW, 2017. Oil palm concessions.
- Gunarso, P., Hartoyo, M., Agus, F., Killeen, T., 2013. Oil palm and land use change in Indonesia, Malaysia and Papua New Guinea. Reports from the Technical Panels of the 2nd greenhouse gas working Group of the Roundtable on Sustainable Palm Oil (RSPO), 29-64.

Hatna, E., Bakker, M.M., 2011. Abandonment and expansion of arable land in Europe. *Ecosystems* 14, 720-731.

Hooijer, A., Page, S., Canadell, J., Silvius, M., Kwadijk, J., Wösten, H., Jauhiainen, J., 2010. Current and future CO<sub>2</sub> emissions from drained peatlands in Southeast Asia.

Miettinen, J., Hooijer, A., Vernimmen, R., Liew, S.C., Page, S.E., 2017. From carbon sink to carbon source: extensive peat oxidation in insular Southeast Asia since 1990. *Environmental Research Letters* 12, 024014.

Miettinen, J., Shi, C., Liew, S.C., 2016. Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990. *Global Ecology and Conservation* 6, 67-78.

OECD/FAO, 2017. OECD-FAO Agricultural Outlook 2017-2026, OECD Publishing.

Plevin, R.J., Beckman, J., Golub, A.A., Witcover, J., O'Hare, M., 2015. Carbon Accounting and Economic Model Uncertainty of Emissions from Biofuels-Induced Land Use Change. *Environmental Science & Technology* 49, 2656-2665.

Schierhorn, F., Müller, D., Beringer, T., Prishchepov, A.V., Kuemmerle, T., Balmann, A., 2013. Post-Soviet cropland abandonment and carbon sequestration in European Russia, Ukraine, and Belarus. *Global Biogeochemical Cycles* 27, 1175-1185.

Taheripour, F., Zhao, X., Tyner, W.E., 2017. The impact of considering land intensification and updated data on biofuels land use change and emissions estimates. *Biotechnology for biofuels* 10, 191.

Terres, J.-M., Scacchiafichi, L.N., Wania, A., Ambar, M., Anguiano, E., Buckwell, A., Coppola, A., Gocht, A., Källström, H.N., Pointereau, P., 2015. Farmland abandonment in Europe: Identification of drivers and indicators, and development of a composite indicator of risk. *Land Use Policy* 49, 20-34.

Tyner, W.E., Taheripour, F., Hoekman, K., Broch, A., Liu, V., Lyons, J., 2016. Follow-on Study of Transportation Fuel Life Cycle Analysis: Review of Current CARB and EPA Estimates of Land use Change (LUC) Impacts. Sierra Research, Sacramento, CA, Coordinating Research Council (CRC).

USB, 2017. Market View Database.

Valin, H., Peters, D., Berg, M.v.d., Frank, S., Havlik, P., Forsell, N., Hamelinck, C., 2015. The land use change impact of biofuels consumed in the EU, European Commission.

Warner, E., Zhang, Y., Inman, D., Heath, G., 2014. Challenges in the estimation of greenhouse gas emissions from biofuel-induced global land-use change. *Biofuels, Bioproducts and Biorefining* 8, 114-125.

Wicke, B., Verweij, P., van Meijl, H., van Vuuren, D.P., Faaij, A.P., 2012. Indirect land use change: review of existing models and strategies for mitigation. *Biofuels* 3, 87-100.

Woltjer, G., Daioglou, V., Elbersen, B., Ibañez, G.B., Smeets, E., González, D.S., Barnó, J.G., 2017. Reporting requirements on biofuels and bioliquids stemming from the directive (EU), EC.