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Estimating induced land use change emissions for sustainable aviation biofuel pathways

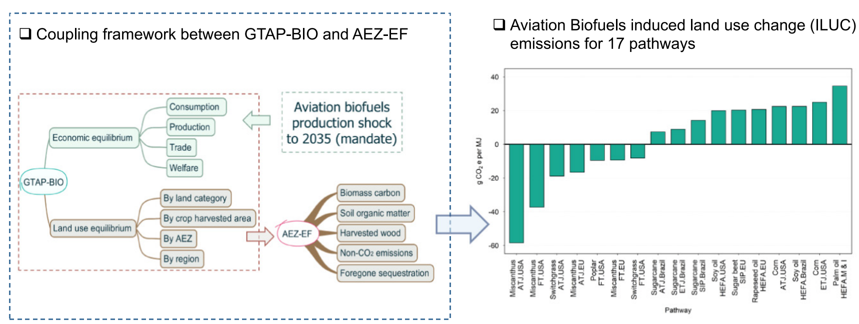
Xin Zhao [a,b,*], Farzad Taheripour [a], Robert Malina [c,d], Mark D. Staples [d], Wallace E. Tyner [a,1]

[a] Department of Agricultural Economics, Purdue University, 403 West State Street, West Lafayette, IN 47907, USA
[b] Joint Global Change Research Institute, Pacific Northwest National Laboratory, 5825 University Research Ct, College Park, MD 20740, USA
[c] Hasselt University, Centre for Environmental Sciences, Agoralaan Building D, BE 3590 Diepenbeek, Belgium
[d] Laboratory for Aviation and the Environment, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

HIGHLIGHTS

- The use of biojet fuels could contribute to aviation emission reductions.
- Biojet induced land use change (ILUC) emissions play a key role in the life-cycle.
- We estimate ILUC emission intensities for 17 biojet pathways using a CGE model.
- The estimated ILUC emission intensities ranging from −58.5 to 34.6 g CO_2e MJ^{-1}.
- Most (15) pathways resulted in lower life-cycle emissions than petroleum fuels.

GRAPHICAL ABSTRACT



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ABSTRACT

Sustainable aviation fuels (SAFs) are expected to play an essential role in achieving the aviation industries' goal of carbon-neutral growth. However, producing biomass-based SAFs may induce changes in global land use and the associated carbon stock. The induced land use change (ILUC) emissions, as a part of the full life-cycle emissions for SAF pathways, will affect whether and to what extent SAFs reduce emissions compared with petroleum-based jet fuels. Here, we estimate the ILUC emission intensity for seventeen SAF pathways considered by the International Civil Aviation Organization (ICAO), covering five ASTM-certified technologies, nine biomass-based feedstocks, and four geographical regions. We introduce the SAF pathways into a well-established computable general equilibrium (CGE) model, GTAP-BIO, and its coupled emission accounting model, AEZ-EF, to study economy-wide implications of SAF production and estimate ILUC emissions intensity for each pathway. The estimated SAF ILUC emission intensities, using a 25-year amortization period, range from −58.5 g CO_2e MJ^{-1} for the USA miscanthus alcohol (isobutanol)-to-jet (ATJ) pathway to 34.6 g CO_2e MJ^{-1} for the Malaysia & Indonesia palm oil Hydrotreated Esters of Fatty Acids (HEFA) pathway. Notably, the vegetable oil pathways tend to have higher ILUC emission intensities due to their linkage to palm expansion and peatland oxidation in Southeast Asia. The cellulosic pathways studied provide negative ILUC emissions, mainly driven by the high carbon sequestrations in crop biomass and soil. Using the core life-cycle emissions established by ICAO, we show that fifteen of the assessed pathways have a lower full life-cycle emission intensity than petroleum-based jet fuels (89 g CO_2e MJ^{-1}), offering promising options to reduce aviation emissions.

* Corresponding author at: Joint Global Change Research Institute, Pacific Northwest National Laboratory, 5825 University Research Ct, College Park, MD 20740, USA.
E-mail address: xin.zhao@pnnl.gov (X. Zhao).
[1] Deceased August 2019.

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1. Introduction

The aviation sector currently accounts for over 2% of human-induced emissions (IPCC, 2014). Without any regulatory measure, notwithstanding the near-term impacts of COVID-19, aviation emissions are expected to be more than tripled by mid-century, driven by the sector's strong long-term growth (Fleming and de Lepinay, 2019). To curb aviation emissions, the International Civil Aviation Organization (ICAO) and its Member States agreed to implement a global market-based scheme in the form of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (Hileman et al., 2013; ICAO, 2016). The goal of CORSIA is to achieve carbon-neutral growth in international aviation from 2020. Since other alternative fuels (e.g., hydrogen, liquefied natural gas, or battery-electric) are not yet viable in aviation due to stringent performance and specification requirements, the use of biomass-based drop-in Sustainable Aviation Fuels (SAFs) could play a critical role in achieving this goal (Staples et al., 2018). Several conversion technologies are available to produce drop-in SAFs from biomass-based feedstocks (de Jong et al., 2015; Kandaramath Hari et al., 2015). Upon approval by the American Society for Testing and Materials (ASTM) (ASTM, 2020), the drop-in SAFs can be used in the existing aircraft and airport fueling systems. However, the problem is whether and to what extent SAFs can reduce aviation emissions compared to conventional petroleum-based jet fuels.

Life-cycle analysis (LCA) has been frequently used to evaluate emissions associated with all stages in the production and use of transportation fuels (Elgowainy et al., 2012) (see Fig. S1 for a comparison of life-cycle between conventional jet fuels and biomass-based SAFs). The carbon stored in SAFs is sequestered during biomass feedstock cultivation. However, producing biomass-based feedstocks may generate consequential changes in land use and related carbon stocks (Carriquiry et al., 2019; Hertel et al., 2010; Searchinger et al., 2008; Taheripour et al., 2017c). In particular, producing feedstocks for SAFs on low soil carbon or idle croplands may increase carbon sequestration in soil or vegetation, while cultivating land converted from forest or pasture will likely decrease carbon stocks (Field et al., 2020). Nevertheless, the calculation of emissions based on a direct land requirement for growing SAF feedstocks could be different from induced land use change[2] (ILUC) emissions. Particularly, the estimation of ILUC emissions also considers impacts from economy-wide market-mediated responses, for example, reallocation of land resources across uses, price induced improvements in crop yields, cropland intensifications due to multi-cropping or unused land reversion, shifts in trade patterns of food and agricultural products; substitution between feed crops and SAFs' coproducts (e.g., Distillers' dried grain with solubles (DDGS) and oilseed meals for livestock feed rations), and efficiency improvements in animal-based food products due to changes in the mix of livestock (from ruminant to non-ruminant) induced by increases in supplies of DDGS and meals due to increased production of SAFs (Hertel et al., 2010; Taheripour et al., 2018; Taheripour et al., 2019; Taheripour and Tyner, 2020).

ILUC emissions have been considered in the road biofuels related policy-making process, e.g., US Renewable Fuel Standard (RFS), the California Low Carbon Fuel Standard (LCFS) program, and the EU 2018 Renewable Energy Directive (RED II), and will be a part of the SAF emission estimates for CORSIA. Under CORSIA, life-cycle emissions that exclude ILUC emissions are referred to as core life-cycle assessment (CLCA) emissions. The sum of CLCA emissions and ILUC emissions is defined as the total life-cycle emissions for a SAF pathway. Previous estimates of CLCA emissions indicated, ignoring ILUC emissions, biomass-based drop-in SAFs could considerably reduce emissions compared with petroleum-based jet fuels (Capaz et al., 2020; de Jong et al., 2017; Elgowainy et al., 2012; Klein et al., 2018; Stratton et al., 2011), ranging from 25% to 90% depending on feedstock and technology (ICAO, 2019). However, the ILUC emissions from SAF production have not been examined in the literature. In this paper, we provide the first comprehensive assessment of ILUC emissions for 17 SAF pathways. This study characterizes work that has been used to inform the establishment of ILUC values for SAF pathways at the Committee for Aviation Environmental Protection (CAEP) of ICAO.

In general, biofuel production links agriculture and energy markets as it produces energy outputs using agricultural inputs. Due to interactions between agricultural and energy markets and their links with other economic activities, trade among regions, competition between land using sectors, and other types of market-mediated responses, biofuels ILUC emissions are a global phenomenon that goes beyond the region expanding biofuels production. To estimate SAF ILUC emissions, global land use change induced by the production of these fuels is first estimated using a global economic model. An emission accounting model is then used to calculate greenhouse gas (GHG) emissions associated with the estimated land use changes, including emissions due to changes in foregone sequestration or soil and vegetation carbon.

Biofuels ILUC and the associated emissions have been widely examined in the literature for first- and second-generation biofuels for road transportation, with a focus on a limited number of pathways (Dunn et al., 2013; Havlík et al., 2011; Laborde and Valin, 2012; Taheripour et al., 2017a; Valin et al., 2015a; Vázquez-Rowe et al., 2014). Several papers summarised and reviewed the existing literature in this area (Ahlgren and Di Lucia, 2014; Broch et al., 2013; Khanna and Crago, 2012; Taheripour et al., 2018). These reviews indicated important disparities among models in the baseline assumptions, shock size, simulation approach, and the data used in calculating emissions. More recent literature has noted that the early publications in this field overestimated the land use effects of biofuels due to limited consideration of market-mediated responses, using inadequate databases, or ignoring recent empirically observed land use change patterns across the world (Zilberman et al., 2018).

The experiences with road biofuels demonstrate that (1) ILUC emissions can be a key factor determining the full life-cycle emission intensity of a biofuel pathway, (2) ILUC can vary considerably across biofuel pathways, mainly contingent on technologies and feedstocks, and (3) ILUC emissions are uncertain and sensitive to modeling parameters and assumptions. To our knowledge, no effort has been made to estimate ILUC emissions for aviation biofuels. The ILUC calculation process is more complicated for aviation biofuels than road biofuels. Unlike road transportation biofuels, aviation biofuels are not commercially produced yet. Their production technologies should be incorporated into the model given the different techno-economic specifications. Also, the coproducts of aviation biofuels are different from the coproducts of road transportation biofuels. In addition to the traditional animal feed coproducts, the aviation biofuels pathways may produce road transportation fuels, which need to be considered in the calculation process of ILUC emissions.

In this paper, we extend the existing literature to estimate SAF ILUC emission intensities. We introduce the SAF pathways into a well-established computable general equilibrium (CGE) model, GTAP-BIO, and its coupled emission accounting model, AEZ-EF, to study economy-wide implications of SAF production and estimate ILUC emissions intensity for 17 pathways. In particular, we focus on drop-in SAFs produced in major biofuels producing regions using ASTM approved conversion technologies, i.e., Hydrotreated Esters of Fatty Acids (HEFA), Fischer-Tropsch (FT), Synthesized Iso-Paraffins (SIP), Alcohol (isobutanol)-To-Jet (ATJ), and Alcohol (ethanol)-To-Jet (ETJ), and biomass feedstocks including starch crops, sugar crops, oil crops, and cellulosic crops. The framework developed for estimating SAF ILUC emission intensities can be consistently applied to evaluations of new pathways.

The results of this paper provide important information and implications for policymakers, private stakeholders, and academic researchers on the induced land-use change emission impacts of large-scale SAF production at a detailed SAF-pathway-specific level. The results also

[2] Induced land use change includes both direct and indirect land use change, as the two cannot be distinguished given the complexity of the market-mediated responses.

contribute to the implementation of ICAO's CORSIA scheme aiming to mitigate global aviation emissions. The rest of this paper is structured as follows. Section 2 describes the SAF pathways to be evaluated and develops shocks for simulations. Section 3 introduces the coupled modeling framework between GTAP-BIO and AEZ-EF and discusses major updates made for this study. The results of ILUC and associated emissions are provided in Section 4. In Section 5, we communicate the critical areas of uncertainties based on the sensitivity analysis conducted and discuss the implications of the results. Finally, Section 6 concludes the paper.

2. Material and methods

2.1. SAF pathways

A complete SAF pathway is defined by a combination of fuel conversion technology, feedstock, and producing region. We focus on ASTM approved technologies, including ATJ, ETJ, SIP, HEFA, and FT[3] using land-based biomass feedstocks including corn, sugar crops (sugarcane, sugar beet), oil crops (soybeans, rapeseed, and palm fruit), and cellulosic dedicated energy crops (miscanthus, switchgrass, and poplar). Agricultural and forestry residues, waste tallows, used cooking oil (UCO), municipal solid waste (MSW), and microalgae will not be included in this analysis given the relatively low risk of generating induced LUC emissions. We focus on four regions, including the USA, EU, Brazil, and an aggregated region of Malaysia & Indonesia, since they are leading road biofuels producers and major petroleum jet fuel consumers. Feedstocks used in a region are decided based on the comparative production advantage (e.g., corn in the US and sugarcane in Brazil) or future production potential (e.g., cellulosic crops). Therefore, 17 pathways, shown in Fig. 1, are evaluated in this study.

2.2. SAFs quantitative targets

The size of expansion in each drop-in SAF pathway, or "shock", is determined based on the CORSIA target for 2035. The production targets of the examined pathways follow the International Energy Agency (IEA) 450 Scenario projections from the World Energy Outlook (WEO) (IEA, 2015c). This scenario is the most aggressive scenario developed by the IEA and projects global SAF production in 2025 and 2040 (IEA, 2015a). The 2035 overall SAF production target, 2596 Petajoules (PJ) or 21.2 Billion Gallons Gasoline Equivalent (BGGE), is interpolated linearly based on those projections. The global projection is further allocated to the regional level and across pathways based on WEO (IEA, 2015c) and Southeast Asia energy outlook (IEA, 2015b), taking into consideration feedstock availability, economic feasibility, and coproduct shares of road biofuels. Since there was no commercial-scale SAF production in 2011, the base year of our analyses, the projected production targets in 2035 define the size of the shocks. The developed shocks are presented in Table 1. Additional details about the shock development are discussed in SI Section S1.

The four regions in this study account for about 67% of global SAF production in 2035, 50% of which is assumed to be nonland-based biofuels, i.e., produced using residue, waste, or other nonland feedstocks. In other words, the 17 pathways evaluated in this study are anticipated to account for about 33% of the global SAF production in 2035. These SAF production shocks are used as external drivers in the economic model to assess land use changes. It is also important to note that most SAF pathways also produce renewable diesel and naphtha fractions. The ratio of SAF to other fuel coproducts varies across SAF pathways. For example, about 25% of a typical HEFA energy output is SAF (Pearlson et al., 2013), while 100% of energy output from ATJ, when produced from corn or cellulosic crops, could be SAF. We assume that the non-SAF fuel coproducts of the examined pathways will be used by the road transport sector, and therefore are shocked in conjunction with SAF. The coproduct output quantities can be determined based on the conversion yield implied by the corresponding conversion technology (Table S1).

[3] FT includes both FT- Synthetic Paraffinic Kerosene (SPK) and FT- Synthetic Kerosene with Aromatics (SKA) and the two are not distinguished for estimating ILUC emissions.

2.3. ILUC emission intensity

To be consistent with literature and CLCA analysis, ILUC emission intensity is calculated for each pathway. The simulations conducted in GTAP-BIO for each pathway are independent and defined in a comparative static approach. Land use change results from GTAP-BIO are translated to total ILUC emissions by summing emissions, calculated as the product of land use changes ($\Delta L_{i,\ j,\ k,\ r}$) and associated emission factors ($F_{i,\ j,\ k,\ r}$), across emission categories (i) (see Section 3.2), land transitions (j), Argo-Ecological Zones (AEZs) (k), and regions (r). The ILUC emission intensity is then calculated by weighting total emissions over the amortization period (AP) and total energy output (EO) (Eq. (1)). As a result, the ILUC emission intensity has units of grams CO_2-equivalent per megajoule (g CO_2e MJ^{-1}).

$$\text{ILUC emission intensity} = \frac{\sum_{i,j,k,r} \Delta L_{i,j,k,r} * F_{i,j,k,r}}{AP \times EO} \tag{1}$$

Following the CORSIA emissions accounting approach, an amortization period of 25 years is used by default. Eq. (1) implies that the total emissions are weighted across all energy outputs from a SAF pathway on an energy basis. That is, the energy content in non-fuel energy coproducts (e.g., electricity or biogas) will also be included in the denominator in ILUC emission intensity calculation. Note that only three pathways, including Brazil sugarcane ATJ, Brazil sugarcane SIP, and EU sugar beet SIP pathways have non-fuel energy coproducts (electricity or biogas). It is also important to note that a consequential approach is used to account for all effects on ILUC emissions from energy outputs and non-energy coproducts. For example, the coproduced oil meals affect ILUC by substituting animal feeds and pasture land used in the livestock industry.

3. Modeling framework

3.1. GTAP - BIO model

We start with the latest version of GTAP-BIO, which was documented in Taheripour et al. (2017c) and Taheripour et al. (2017a). This model uses a modified version of the standard GTAP Data Base V9 with the base year of 2011 (Aguiar et al., 2016), including road biofuels technologies (Taheripour et al., 2017b). We modify this model and its database to estimate ILUC emissions for SAF. The major modifications include (1) introducing miscanthus (*Miscanthus sinensis*), switchgrass (*Panicum virgatum*), and poplar (*Populus* spp.) in the database and model, (2) modifying the constant elasticity of transformation (CET) nesting structure of the land supply module to introduce cropland supply for cellulosic crops by nesting miscanthus, switchgrass, and poplar with cropland pasture, (3) incorporating SAF pathways in the database and model based on the information from techno-economic analysis literature, (4) splitting coproducts for SAF in the database and incorporation energy coproducts in the modeling framework, and finally, (5) tuning model parameters related to SAF pathways. The GTAP-BIO model and modifications are described in more details in SI Section S2.

Following Taheripour et al. (2011), the CET land supply nest for cellulosic cropland and cropland pasture is separated from other cropland. The transformation parameters in the new nest reflect that cellulosic crops will more likely be grown on marginal cropland, e.g., cropland pasture. The production and cost data for feedstocks and pathways are drawn from the literature (see SI Section S2). Cellulosic feedstocks are

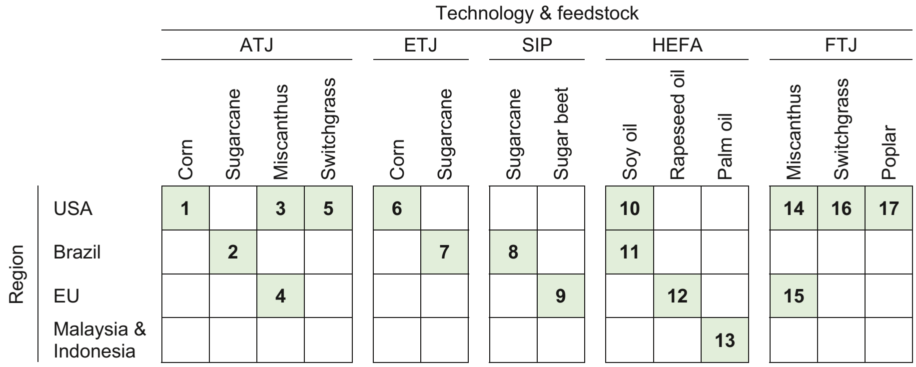

Fig. 1. Sustainable aviation fuel pathways by region, technology, and feedstock for induced land use change emission intensity evaluation.

introduced as intermediate inputs in biofuel production. Leontief production function is used for SAF production in the top (intermediate inputs) nest so that the technology conversion yields remain unchanged in the simulation. All fuel products, either SAF or road biofuels coproducts, are nested with other biofuels and enter the blender industry. The blender industry in GTAP-BIO processes biofuels and blends them with petroleum fuels to supply road or aviation transportation. Other coproducts, including DDGS, electricity, and biogas, are treated the same as the existing products in the model.

Driven by an increase in demand for an agricultural commodity for producing biofuels, there could be market-mediated responses around demand, intensive, and extensive margins (see Fig. S2). The demand margin reflects the market-mediated responses in the global economy due to changes in consumption and trade. As a response to higher crop prices encouraged by biofuel production, households and firms will reduce their crop consumption or increase the consumption of their substitute. There are similar substitution responses when coproducts are being supplied. For example, a higher oilseed meals supply could increase this feed item in the livestock industry and allow this industry to use less pasture or feed crops. These effects could transfer to other countries through international trade. The intensive margin includes intensifications in crop production as a response to an increase in the commodity price through (1) substituting land with other inputs in production, (2) multiple cropping practices or use of existing cropland, and (3) technological improvements.[4] Finally, the expansion in extensive margin implies land transformation from forest, pasture, or other crops to producing biofuel feedstocks. When land is converted from forest or pasture to cropland, the productivity of the land will likely be different from the existing cropland. Also, land transformations directly affect the supply and demand of other land-using industries (i.e., other crops, livestock, forestry) due to the scarcity of land endowment. As a result of the domestic and international interactions and responses, land conversion from forest and pasture to cropland in each region could be accounted as land use change induced by biofuel production.

Table 1
Shock size for sustainable aviation fuel pathways.

Region	Feedstock	Technology	SAF (PJ)	Fuel coproduct (PJ)	Total (PJ)
USA	Soy oil	HEFA	57	171	228
	Corn	ATJ	104	0	104
	Corn	ETJ	104	32	136
	Miscanthus	FT	69	208	277
	Miscanthus	ATJ	69	0	69
	Switchgrass	FT	69	208	277
	Switchgrass	ATJ	69	0	69
	Poplar	FT	69	208	277
Brazil	Soy oil	HEFA	44	132	177
	Sugarcane	SIP	104	0	104
	Sugarcane	ATJ	104	14	118
	Sugarcane	ETJ	104	65	169
EU	Rapeseed oil	HEFA	65	195	260
	Miscanthus	FT	52	156	208
	Miscanthus	ATJ	52	0	52
	Sugar beet	SIP	78	0	78
Malaysia & Indonesia	Palm oil	HEFA	52	156	208

Note: 1 Petajoule (PJ) = 1 billion Megajoules (MJ) and 1 PJ = 0.008 Billion Gallons Gasoline Equivalent (BGGE).

3.2. AEZ-EF model

The AEZ-EF model is an emission accounting model for translating LUC results from GTAP-BIO to the ILUC emission intensities (Plevin et al., 2011). The latest version of the model was designed to process land use change results from GTAP-BIO into transition matrices and then apply emission factors by transitions in each region and AEZ and for each emission category (Plevin et al., 2014). We decompose the ILUC emission into several categories to communicate results (see Table 2). For this study, the AEZ-EF model was modified to introduce cellulosic crops,[5] update palm related assumptions and emission factors, and account for emissions from converting unused land (see SI Section S3 for details).

4. Results

An overview of the ILUC emission intensity values for the 17 SAF pathways is presented in Fig. 2. The results indicate a wide range of ILUC emission intensities across the examined pathways from −58.5 (USA miscanthus ATJ) to 34.6 (Malaysia & Indonesia palm oil HEFA) g CO_2e MJ^{-1}. Feedstock appears to be the most important driver of the variations across pathways compared to region and technology. To interpret results and facilitate comparison, the pathways are categorized into three groups by feedstocks: (1) starch & sugar crops, (2) vegetable oil crops, and (3) cellulosic crops. On the one hand, vegetable oil pathways are estimated to have the highest ILUC emissions on average (24.4 g CO_2e MJ^{-1}), mainly because of the direct or indirect linkages to the high deforestation and peat oxidation in Southeast Asia driven by palm expansion. Thus, it is not surprising that palm oil HEFA produced in Malaysia & Indonesia has the highest ILUC emission score. On

[4] This may include a wide array of technologies that increase yield. This response is currently only implemented for cropland pasture as an endogenous response in GTAP-BIO.

[5] The modifications for adding cellulosic crops were completed in collaboration with Dr. Richard Plevin, one of the developers of the CARB AEZ-EF model. The changes were made in the Python version of AEZ-EF. Some important emission factors and assumptions were then updated to reflect the new literature data (See SI Section S3).

Table 2
Emission categories for induced land use change emission calculations in AEZ-EF.

Emission category	Interpretation
Natural vegetation	Carbon in above and below ground living biomass for forest, pasture, cropland pasture. For forest, both models also consider dead wood, litter, understory, litter, and harvested wood products.
Foregone sequestration	This category accounts for foregone sequestration from converting forest. It assumed that forest if not converted can still sequestrate carbon at a certain rate.
Unused cropland	The latest GTAP-BIO allows increasing the use of unused cropland as a land source for crops (biofuels feedstock) production. The unused cropland may have carbon stock in the natural vegetation grown on the land, and it may have higher carbon sequestrated in soil compared with the cropland under cultivation. Thus, there could land use change emissions from bringing unused cropland back to production. In this study, we assume that the emission factors for unused cropland are the same with those for cropland pasture.
Agricultural biomass	Agricultural biomass carbon accounts for carbon changes in agricultural biomass including aboveground and belowground (root and rhizome) biomass. Crop yield, root-to-shoot ratio, harvest index, and effective carbon fraction are key factors in determining the agricultural biomass carbon.
Soil organic carbon	Soil organic carbon (SOC) accounts for carbon changes in soil. Natural land (e.g., forest and pasture) usually have significantly higher SOC compared with cropland. SOC sequestration in land growing perennial crops is much higher than in land growing annual crops. Peatland oxidation is not included here.
Peatland oxidation	Peatland oxidation is separated from soil organic carbon given the importance. It accounts for soil emissions from peatland drainage in Indonesia and Malaysia.

the other hand, all the cellulosic pathways show negative ILUC emission intensities, with an average of −22.6 g CO_2e MJ^{-1}, owing to the high soil carbon sequestration and biomass carbon from producing cellulosic crops. In other words, SAF produced from these pathways could also provide carbon credits through land use change (Field et al., 2020). In addition, the average emission intensity from the six starch & sugar pathways is 16.4 g CO_2e MJ^{-1}.

In the following sections, more detailed results for each pathway group are discussed with the decomposition of ILUC and associated emissions. In particular, biofuels induced global harvested area increase in the feedstock, weighted by energy output, is decomposed into land supply sources, including a reduction in areas of other crops (crop switching), cropland intensification (multi-cropping & unused cropland), cropland pasture, pasture, and forest. The emission intensity of each pathway is also decomposed by emission sources (see Table 2), including carbon in natural vegetation, foregone sequestration & unused cropland, agricultural biomass, soil organic carbon, and peatland oxidation. The regional land use change results for all pathways are presented in Tables S10–S26, and the decomposed total ILUC emissions are presented in Table S27.

4.1. Starch and sugar pathways

The decompositions of ILUC and associated emissions for starch and sugar pathways are presented in Fig. 3. The pathways are further grouped by regions or feedstocks in presenting the results since only one crop is used in a study region. And the different ILUC emissions across pathways using the same feedstock in the same region can be mostly explained by the difference in technology conversion yield.

For producing 104 PJ ATJ fuels in the USA, 14.4 million tons (Mt) of corn is directly needed, while 4.4 Mt. DDGS is coproduced for substituting corn or other feed crops in livestock sectors. As a result of the substitution in livestock sectors and other demand responses, GTAP-BIO projects that global corn production increases by 9.4 Mt., and 91% of the increase is grown in the USA. The shock of 104 PJ USA corn ATJ fuels leads to a 1.04 Mha increase in the global coarse grains area (i.e., 10 Kha/PJ shown in Fig. 3a). The decomposition indicates a strong decrease in other crop areas, or crop switching (0.59 Mha or 5.7 Kha/PJ). Cropland pasture accounts for 0.21 Mha (or 2 Kha/PJ), and multi-cropping and unused cropland provides 0.12 Mha (or 2 Kha/PJ) with the rest supplied by forest and pasture. The model projects little land conversion from forest and pasture in the USA, while Sub-Saharan Africa (−52 Kha), Brazil (−19 Kha), and other South American countries (−11 Kha) are major regions of deforestation and pasture conversion. The total ILUC emissions driven by the global land use change are estimated to be 58 $MtCO_2$, translating to an emission intensity of 22.5 g CO_2e MJ^{-1}. Emissions from changes in natural vegetation (45%) and SOC (37%) are the largest sources (together accounting for 48 $MtCO_2$ or 18.5 g CO_2e MJ^{-1}), followed by emissions from converting unused land (2.4 g CO_2e MJ^{-1}) and foregone sequestration (1.5 g CO_2e MJ^{-1}). The carbon sequestration in agricultural biomass carbon (−0.3 g CO_2e MJ^{-1}) is small since corn mainly expands into other crops or cropland pasture. Carbon sequestered in newly expanded corn is comparable in magnitude to carbon previously stored in the converted crops or cropland pasture. In addition, emissions from peatland

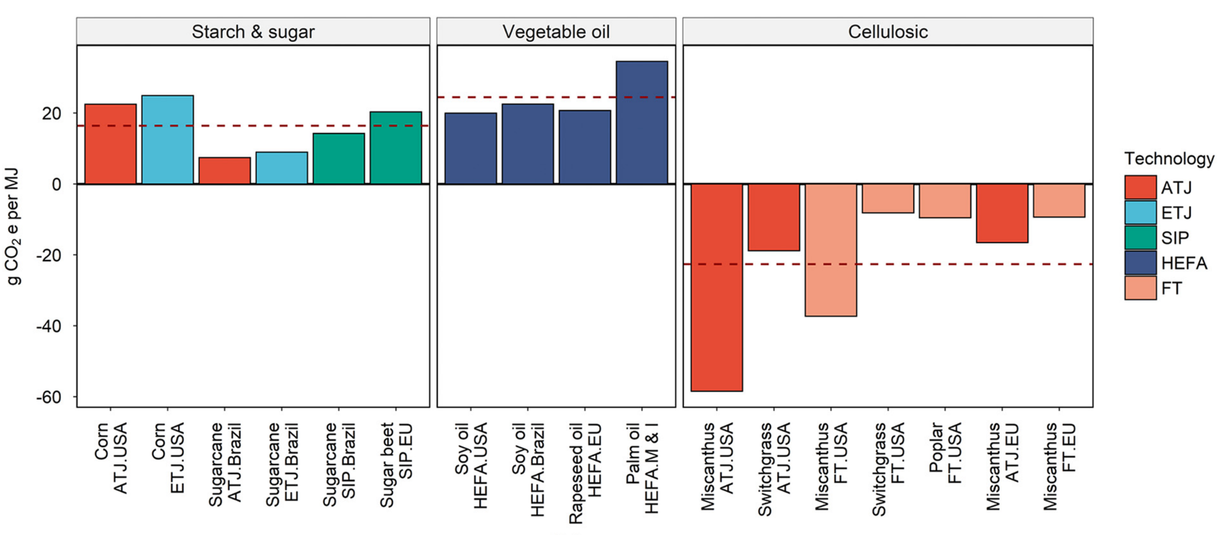

Fig. 2. Induced land use change (ILUC) emission intensity for sustainable aviation fuel pathways. Bars show the 25-year ILUC emission intensity (in g CO_2e/MJ) across 17 pathways, with technologies distinguished by color, estimated using GTAP-BIO and AEZ-EF. Note that "M & I" represents Malaysia and Indonesia. See Table S2 for data.

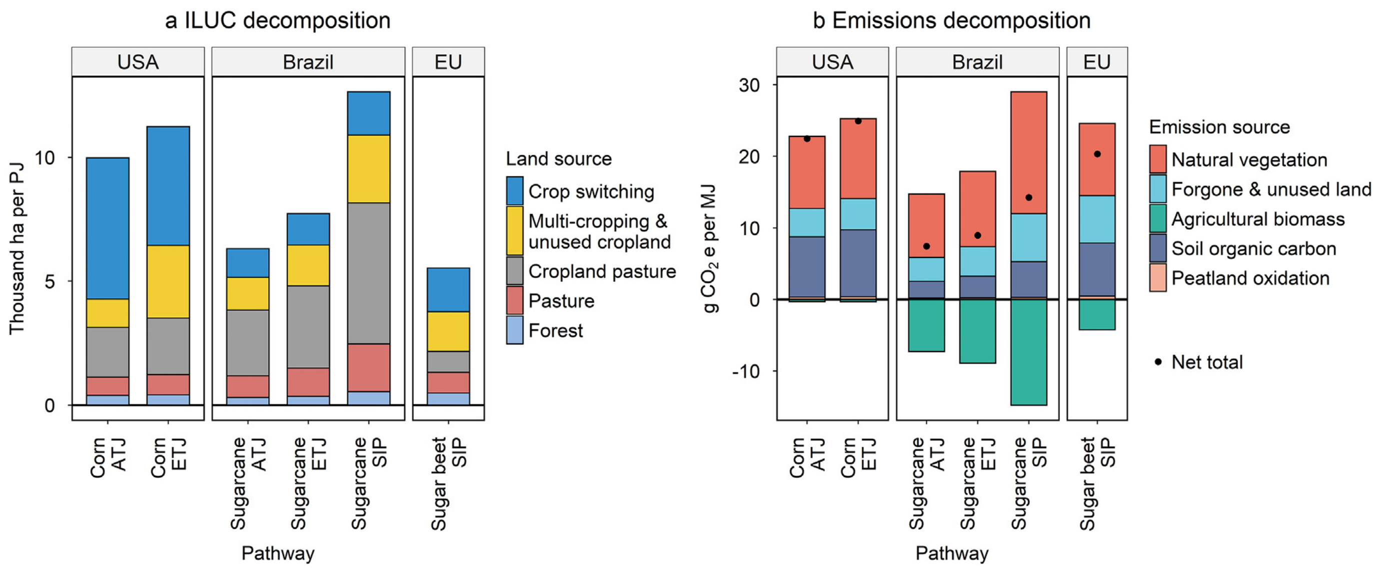

Fig. 3. Decomposition of induced land use change (ILUC) and associated emissions from starch or sugar crops based sustainable aviation fuel pathways. The total bar level in Fig. 3a for a pathway indicates the biofuels induced global harvested area increase in the feedstock, weighted by energy output, which is decomposed by five sources (distinguished by the color of stacked bars) of land supply. The net total bar level and the point in Fig. 3b for a pathway represents the biofuel induced ILUC emission intensity increase, which is decomposed by five sources (distinguished by the color of stacked bars) of emissions.

oxidation are negligible since the market-mediated impacts on palm oil production in Malaysia and Indonesia are negligible in the corn ATJ and other starch & sugar pathways. This is consistent with findings from Taheripour and Tyner (2020). Compared with USA corn ATJ, corn ETJ has about 12% higher global coarse grains expansion (11 Kha/PJ) and 11% higher ILUC emissions (24.9 g CO_2e MJ^{-1}). The difference can be mostly explained by the 10% lower fuel conversion yield and slightly lower DDGS coproduct yield in the corn ETJ pathway.

Compared with USA corn, using Brazil sugarcane in the ATJ and ETJ pathways results in smaller cropland expansion and ILUC emissions, mainly driven by (1) the higher overall conversion yield (feedstock & technology) and (2) higher carbon sequestrations in crop biomass and soil for sugarcane (a perennial crop with high dry matter biomass yield) compared to annual crops like corn or sugar beet. For the example of Brazil sugarcane ATJ, the 118 PJ shocks of fuels require 67.4 Mt. of sugarcane. The demand drives a global increase in sugarcane production of 66.2 Mt., almost entirely grown in Brazil. This shock, with 139 PJ of energy output (including 21 PJ electricity), leads to a 0.88 Mha increase in the global sugarcane area (i.e., 6.3 Kha/PJ shown in Fig. 3a). Crop switching plays a relatively less important role in area supply for Brazil sugarcane ATJ, e.g., accounting for 18% vs. 57% in US corn ATJ, because no feedstuff coproducts for additional substitutions are produced in sugar pathways, and, thus, other sources of land supply had higher contributions, e.g., 2.7 Kha/PJ from cropland pasture and 1.3 Kha/PJ from cropland intensification. Total ILUC emissions from the Brazil sugarcane ATJ shock are 25 $MtCO_2$, and the emission intensity is 7.4 g CO_2e MJ^{-1}. Emissions from natural vegetation dominate total emissions (8.9 g CO_2e MJ^{-1}), much of which is compensated by sequestration in agricultural crop biomass (−7.3 g CO_2e MJ^{-1}). SOC emissions are relatively small (2.3 g CO_2e MJ^{-1}), mainly because of the offset from the higher SOC in sugarcane. Emissions from converting unused land and foregone sequestration contributed 2.3 and 1.1 g CO_2e MJ^{-1}, respectively. In addition, the land use change and emission decomposition patterns are similar for the three Brazil sugarcane pathways. The land use change and associated emissions are inversely proportional to the energy conversion yield of the technology, e.g., sugarcane area expansion and ILUC emission intensity from the Brazil SIP pathway approximately doubled the corresponding values estimated for the Brazil ATJ pathway, as the technology conversion yield of SIP was about half of the yield of ATJ pathway.

Sugar beet SIP has a significantly higher conversion yield, particularly when considering the energy content in the biogas coproducts of the sugarcane SIP pathway. The 147 PJ energy output (including 69 PJ coproduct) from the EU sugar beet SIP shock leads to 63 Mt. sugar beet expansion, entirely in the EU. It also results in a cropland expansion of 5.5 Kha/PJ, much smaller than the 12.7 Kha/PJ in the Brazil sugarcane SIP pathway. However, the ILUC emission intensity of EU sugar beet SIP (20.3 g CO_2e MJ^{-1}) was higher than Brazil sugarcane SIP (14.2 g CO_2e MJ^{-1}), primarily due to lower crop biomass carbon and higher SOC.

4.2. Vegetable oil pathways

The decompositions of ILUC and associated emissions for vegetable oil pathways are presented in Fig. 4. All four vegetable oil pathways used HEFA technology, and they all produce feedstuff coproducts to supply livestock sectors. Furthermore, due to substitutions among vegetable oils and international trade, producing biofuels from any vegetable oil in any region would encourage palm oil expansion and associated peat oxidation in Malaysia and Indonesia. However, there are differences in regional specifications of feedstock yield and land mix, oilseed crushing rate, and the magnitude of connection to peat oxidation across pathways, resulting in different ILUC emission estimates.

For the USA soy oil HEFA pathway, to meet the shock of 228 PJ HEFA fuels, 6.3 Mt. of soy oil is directly needed. Soybeans have a crushing rate of about 19% (by weight) soy oil and 80% soy meal. The coproduced soy meal enters livestock sectors as protein feedstuff. In addition to the newly crushed soy oil, substitutions among vegetable oils, increases in the share of oilseeds being crushed, and vegetable oil consumption reductions play an essential role in supplying the soy oil feedstock. As a result of market-mediated responses, GTAP-BIO projects that global soybean production increases by 9.1 Mt., with 93% occurring in the USA. After considering about 1% endogenous yield increase induced by biofuel shocks at the world level (about 2% in the USA) for soybeans, the production expansion leads to a 2.54 Mha increase (i.e., 11.1 Kha/PJ shown in Fig. 4a) in the global harvested area for soybeans. The decomposition indicates that crop switching (8.2 Kha/PJ) plays the most important role in supplying soybeans land, driven by the substitution effects from the coproduced soy meal. Cropland pasture accounts for 1.45 Kha/PJ, and multi-cropping and unused cropland supplies 0.7 Kha/PJ with the rest provided by forest (0.2 Kha/PJ) and pasture

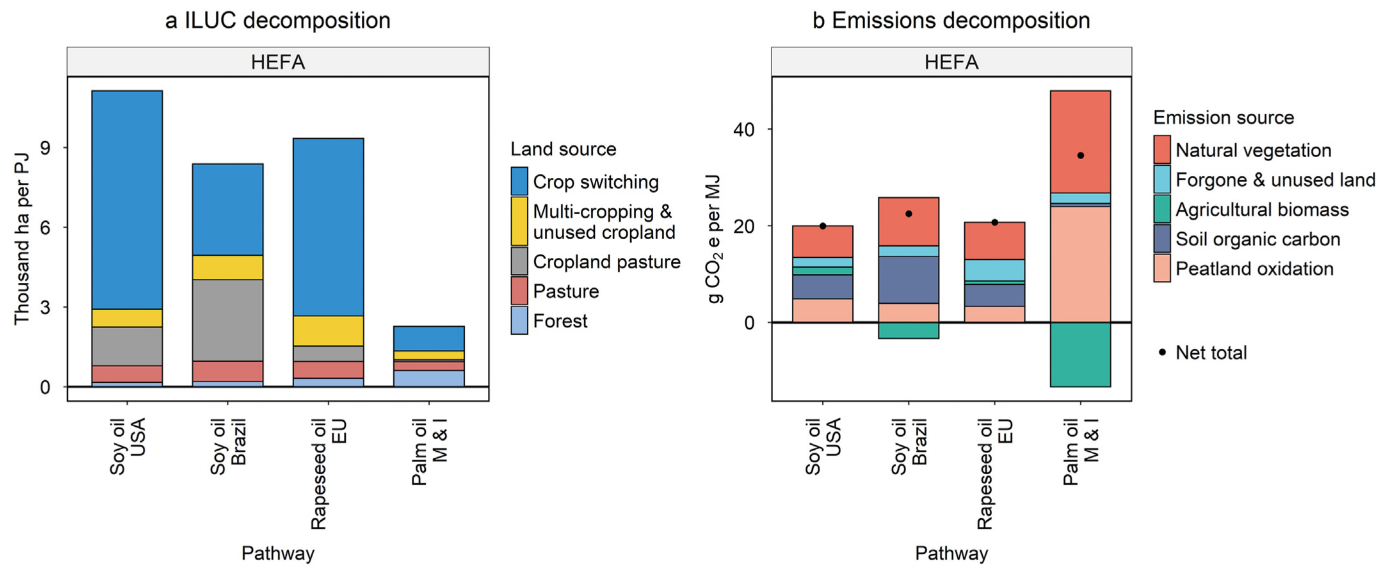

Fig. 4. Decomposition of induced land use change (ILUC) and associated emissions from vegetable oil based sustainable aviation fuel pathways. Note that "M & I" represents Malaysia and Indonesia. See Fig. 3 caption for additional description.

(0.6 Kha/PJ). Total ILUC emissions from the USA soy HEFA shock are 114 $MtCO_{2,}$ and the emission intensity is 20 g CO_2e MJ^{-1}, mainly driven by emissions from natural vegetation (6.5 g CO_2e MJ^{-1}) and SOC (5 g CO_2e MJ^{-1}). It is also important to note that peat oxidation in Southeast Asia is also a key emission contributor (4.9 g CO_2e MJ^{-1}) since palm area expands in Malaysia & Indonesia by about 0.4 Kha/PJ, due to substitutions between vegetable oils.

Compared to USA soy oil HEFA, the simulation results indicated higher overall conversion yield (feedstock & technology) and/or stronger market-mediated responses for the Brazil soy oil HEFA and EU rapeseed oil HEFA pathways, given relatively smaller global feedstock expansion, i.e., 8.4 Kha/PJ in Brazil soy oil HEFA and 9.4 Kha/PJ in EU rapeseed oil HEFA. Note that, compared to the USA, both higher soybean yield in the base data and stronger yield responses in Brazil played key roles in explaining the lower soybean area expansion. Soybean expansion in Brazil relies relatively more on cropland pasture as opposed to crop switching, which explains both higher sequestrations in crop biomass carbon and higher emissions from natural vegetation and SOC. The emission intensity from the soy oil and rapeseed oil pathways are comparable, 20–22.5 g CO_2e MJ^{-1}.

For the Malaysia & Indonesia palm oil HEFA pathway, 5.7 Mt. palm oil is required for producing the shock of 208 PJ HEFA fuels. The crushing rate for palm fruit is about 24% (by weight) for palm oil and palm kernel oil together. There is also about 3% palm kernel meal supplying livestock sectors. GTAP-BIO estimates the global palm fruit production increases by 9.1 Mt., and 89% of the increase is produced in Malaysia and Indonesia. As a result, the global oil palm cultivated area increases by 0.47 Mha or 2.3 Kha/PJ, of which forest and pasture contribute 43%, and crop switching accounts for 40%. Regardless of the highest overall conversion yield (feedstock & technology) among all oilseeds, the ILUC emission intensity is the highest among the vegetable oil pathways (34.6 g CO_2e MJ^{-1}). The shock leads to 0.37 Mha palm expansion in Malaysia & Indonesia, of which 33% is assumed to expand on peat swamp forest or grassland (Edwards et al., 2010). High ILUC emissions from this pathway are mainly explained by tropical deforestation and peat oxidation due to SAF induced palm expansion, i.e., 24 g CO_2e MJ^{-1} from peatland oxidation and 21.1 g CO_2e MJ^{-1} from nature vegetation changes. As perennials, Palm trees also have high sequestrations in biomass carbon and SOC, partly compensating for deforestation and peat oxidation.

4.3. Cellulosic pathways

The decompositions of ILUC and associated emissions for cellulosic pathways are presented in Fig. 5. Cellulosic crops are modeled as dedicated energy crops. The increase in total cellulosic crop production is equal to the shock requirement for each pathway. For example, 34.1 Mt. of miscanthus was needed to produce 277 PJ FT fuels in the USA. With the assumed average dry matter yield of 18.8 t/ha for miscanthus in the USA and 20% post-harvest loss, the miscanthus harvested area would be 2.25 Mha or 8.1 Kha/PJ. Because there is no demand or substitution response for dedicated energy crops, the estimated increase in cellulosic cropland is determined by the overall conversion yield (feedstock & technology) and the shock size.

Cropland pasture is a major land source in the USA, while unused cropland and natural land play relatively more critical roles in the EU cellulosic pathways. Given the considerable biomass carbon and SOC sequestration from growing cellulosic crops, relative to other row crops or even pasture, the total ILUC emissions from these cellulosic pathways are negative, implying net carbon sequestration. A cellulosic pathway with higher feedstock yield or technology conversion yield would result in lower feedstock area expansion. The conversion technology yields in cellulosic ATJ pathways are generally lower than the corresponding FT pathways using the same feedstock (by around 30%), which largely explains the higher land use change but lower emission intensities for ATJ vs. FT. The sensitivity of cellulosic crop yield, biomass carbon, and SOC is discussed in Section 5, given the high uncertainty in these key parameters.

5. Discussion and implications

ILUC and associated emissions cannot be directly observed, but they can be estimated using global economic models in a comparative manner (i.e., with vs. without biofuel shocks) as we have undertaken in this study. However, the estimation is subject to uncertainties around data, parameters, and model design. Here, we conduct a sensitivity analysis for some key data and parameter assumptions in GTAP-BIO and AEZ-EF for estimating SAF ILUC emissions. To avoid repetitive results, we show results here for a representative subset of all the SAF pathways (11 of 17): pathways using the same feedstock in the same region are reduced to one pathway. For example, only SIP in the three Brazil sugarcane pathways is tested for sensitivity since the knowledge learned can

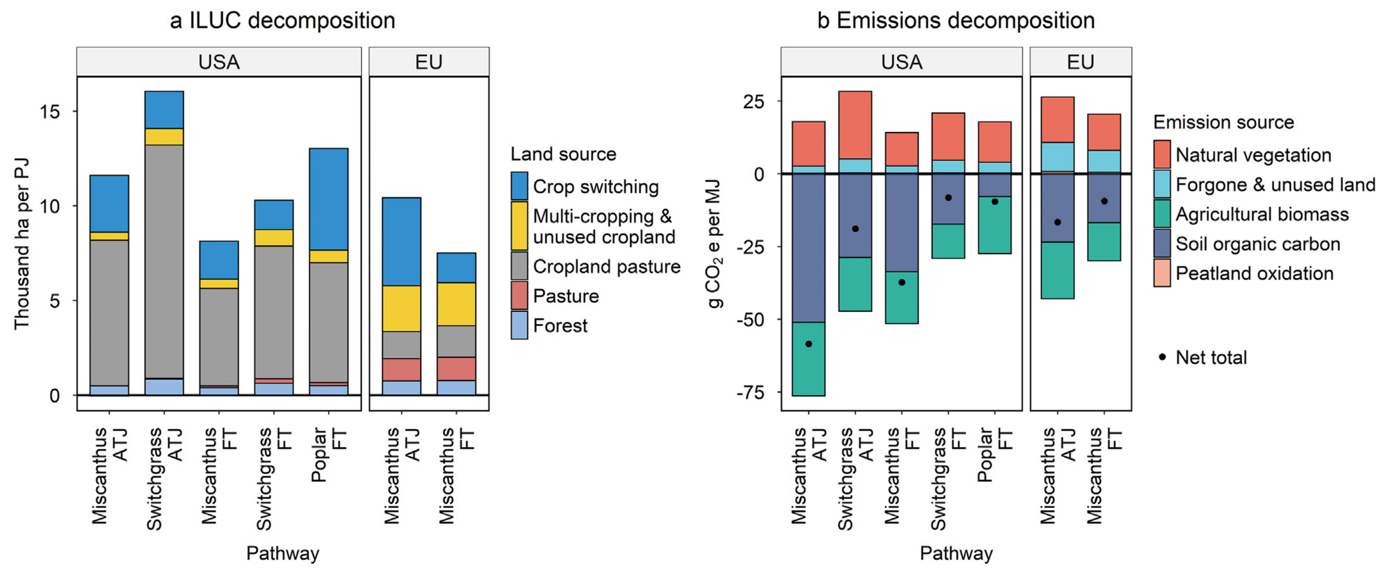

Fig. 5. Decomposition of induced land use change (ILUC) and associated emissions from cellulosic crops based sustainable aviation fuel pathways. See Fig. 3 caption for additional description.

be applied to the other two (ATJ & ETJ). The experimental design is presented in Fig. S3. For each group of pathways, we select the most important parameters or assumptions used in estimating ILUC emission intensities to investigate how results are affected by extreme or representative scenarios of these parameters or assumptions. Besides the key parameters that influence market-mediated responses and those which affect emission factors, sensitivity tests on shock size and different amortization periods are explored as well. The implications of the ILUC emission score on the full life-cycle emissions are also discussed.

5.1. Key market-mediated responses

The sensitivity of several important parameters in GTAP-BIO, including crop yield price elasticity (YDEL), extensive margin elasticity (ETA), and trade (Armington) elasticity, governing the magnitude of key market-mediated responses, are investigated for starch, sugar, and vegetable oil pathways. The sensitivity of these parameters is not tested for cellulosic pathways because cellulosic crops are modeled as dedicated energy crops for SAF production with no international trade, and the cellulosic crop yields are fixed in simulations.

YDEL governs the elasticity of endogenous crop yield with respect to crop prices (Keeney and Hertel, 2009). The modeling mirrors the fact that agricultural producers would invest in yield improvements to increase yield when crop prices increase. In a recent study from Taheripour et al. (2017a), the uniform YDEL value (0.25) used in GTAP-BIO was differentiated across regions and calibrated based on historical observations of productivity improvements (e.g., 0.3 for the USA, 0.325 for Brazil, 0.25 for EU, and 0.3 for Malaysia & Indonesia). These values are used in the default scenario for all crops in a region, except that 0.05 was used for palm fruit in Malaysia & Indonesia. ETA in GTAP-BIO governs the productivity ratio between newly converted land and the existing cropland. The parameters were derived using the net primary productivity (NPP) information at the AEZ and region levels (Taheripour et al., 2012). The default ETA values range from 0 to 1, where 0 indicates no productive land is available in an AEZ of a region, and 1 suggests that newly converted land is equally productive as the existing cropland. Armington elasticity measures the degree of substitutability between home and imported goods. In general, larger Armington elasticities imply that products produced from different origins are more homogeneous to the consumer. The model would be closer to a Heckscher-Ohlin model of homogeneous goods as Armington elasticities grow. GTAP models employ a nested Armington structure for bilateral trade with empirically estimated parameters (Hertel et al., 2007). There are two Armington parameters for each commodity, respectively governing "foreign – foreign" and "home – foreign composite" substitutions.

In sensitivity scenarios, we follow the format and parameter ranges used in a previous analysis (Tyner et al., 2016). For YDEL, we test alternative values for all crops in the four studying regions, of 0.05 for a low and 0.35 for a high yield elasticity scenario. For ETA, we test a low new cropland productivity scenario using 80% of the default ETA values and a high productivity scenario using 120%[6] of the default ETA values for all AEZs and regions. For Armington elasticities at both nesting levels, we test scenarios using 50% (low trade responses) and 150% (high trade responses) of the default parameters for agricultural, livestock, and forestry sectors. The results from the sensitivity tests of key model parameters are shown in Fig. S4.

As expected, either higher yield elasticity or higher new land productivity results in higher crop yields and, thus, reduced ILUC emissions. Since the default YDEL values for the four regions are generally closer to the upper value (0.35), except for palm in Malaysia & Indonesia, ILUC emissions did not decrease significantly in the high YDEL scenario. Conversely, ILUC emissions increase considerably in the low YDEL scenario except for the Malaysia & Indonesia palm oil HEFA pathway. The average ILUC emission intensity range from YDEL sensitivity tests across the seven pathways is 8.8 g CO_2e MJ^{-1}, which is 40% of the average default estimates (22.1 g CO_2e MJ^{-1}) and about 10% of the life-cycle emission intensity of petroleum-based jet fuels (89 g CO_2e MJ^{-1}). The average ILUC emission intensity range from ETA sensitivity tests is 7.2 g CO_2e MJ^{-1}, comparable to the average value from YDEL tests. However, there is a negative correlation of emission intensities between YDEL and ETA across the pathways. It appears pathways with higher sensitivity to ETA (e.g., Brazil and Malaysia & Indonesia pathways) tend to have relatively more land expansion on natural land. In contrast, pathways more sensitive to YDEL rely more on crop switching. In other words, intensive and extensive yield margins may compensate each other in their contributions to parameter uncertainty (Zhao et al., 2020).

The average ILUC emission intensity range from Armington parameters sensitivity tests across the seven pathways is 4.4 g CO_2e MJ^{-1}, and

[6] We allow ETA to be greater than 1 in the sensitivity test to reflect extreme cases that new cropland could have higher productivity than the average of existing cropland.

the results indicate heterogeneous impacts from across pathways/regions. For the USA and EU pathways, higher Armington parameter values increase accessibility to the international market so that relatively more feedstock would be produced internationally in regions with lower crop yield and higher deforestation rates. However, it was the opposite for the palm oil pathway in Malaysia & Indonesia, in which higher Armington elasticities permit a more substantial reduction in palm oil exports and effectively increase the substitution from other vegetable oils. As a result, less palm oil is produced, leading to reduced peat oxidation and tropical deforestation. The case for Brazil soy oil HEFA is similar to Malaysia & Indonesia palm oil HEFA. Brazil has a relatively higher deforestation rate and associated emission factors compared with its soy oil producing competitors (e.g., the USA). Furthermore, the impact of Armington elasticities on the sugarcane SIP pathway in Brazil is negligible, mainly because sugarcane is not directly traded and the effect of the shock on global sugar markets is small.

5.2. Palm expansion and peat oxidation

The peatland ecosystem is one of the world's richest carbon sinks, as it accumulates decayed vegetation or organic matter over thousands of years (Hugron et al., 2013). Drainage of peatlands, peat swamp forests mainly, for industrial oil palm plantation in Malaysia and Indonesia (FAOSTAT, 2020) leads to considerable soil carbon loss. Due to substitutions among vegetable oils and international trade, producing SAF from any vegetable oil in any region could encourage palm oil expansion in Malaysia and Indonesia. In other words, ILUC emissions results, particularly for vegetable oil pathways, are very sensitive to the palm related parameters.

The default peat oxidation factor in this study, 38.1 t CO_2/ha/year, is calculated based on recent data provided by Miettinen et al. (2016) and Miettinen et al. (2017). Given the high uncertainty, we test three scenarios for the peat oxidation factor: (1) a low scenario of 30.8 t CO_2/ha/year, which was calculated based on a recent study from Austin et al. (2017), (2) a high scenario of 60.8 t CO_2/ha/year, which was the mean value used in Valin et al. (2015b), and (3) an extreme scenario of 95 t CO_2/ha/year from Page et al. (2011), which was also the value used in previous versions of AEZ-EF. Furthermore, AEZ-EF assumes 33% palm expansion in Malaysia and Indonesia would be on peatland based on assumptions made in Edwards et al. (2010). We also test an alternative scenario assuming 20% palm expansion on peatland in Malaysia and Indonesia, as implied by trends in more recent data (Austin et al., 2017).

The sensitivity test results (Fig. S5) demonstrate a significant impact of the peat oxidation factor on ILUC emission intensities for HEFA pathways but fairly small impacts on results of other pathways (+2 to 3% under the extreme scenario for starch & sugar pathways). With the extreme value of peat oxidation, the ILUC emission intensity is doubled for the Malaysia & Indonesia palm oil HEFA pathway and increases by about 25%–30% for the other vegetable oil HEFA pathways. Like peat oxidation factors, decreasing palm expansion on peatland has a negligible impact on non-HEFA pathways but reduces ILUC emission intensity for HEFA pathways significantly (i.e., −6 to 27%). Given the increasing government and international attention to deforestation and peatland drainage in Southeast Asia, both the peat oxidation factor and the share of palm expansion on peatland have the potential to decrease in the future, which would reduce ILUC emissions for the HEFA pathways.

5.3. Cellulosic crop yield and emission factors

Cellulosic crops are not currently produced at a commercial-scale and are expected to be produced only for bioenergy uses. Cellulosic crops are also modeled with fixed average crop yields. Therefore, the market-mediated responses are negligible for these pathways compared with pathways using regular crops. Cellulosic crop yield, soil organic carbon (SOC), and agricultural biomass carbon are three critical factors driving the ILUC emission results for cellulosic pathways. In the default scenario, the after-loss dry yields for cellulosic crops are 15.0 t/ha for US miscanthus, 11.4 t/ha for US switchgrass, 8.5 t/ha for US poplar, and 16.5 t/ha for EU miscanthus. Literature emission factors for SOC and biomass carbon are used for cellulosic crops. We examine the sensitivity of ILUC emission intensity of cellulosic pathways to ±20% of the default cellulosic crop yield, ± 30% of the default SOC emission factors, and ± 30% of the default cellulosic biomass carbon.

The sensitivity results are shown in Fig. S6. For switchgrass and poplar pathways, just like other pathways using regular crops, an increase in crop yield reduces land conversion from natural vegetation and related emissions. However, it is different for miscanthus since converting pasture or even forest for miscanthus cultivation could increase SOC sequestration in many AEZs. Thus, a lower miscanthus crop yield entails relatively more land being converted for the crop and higher total SOC sequestration. The ILUC emissions impacts from SOC and biomass carbon are symmetric around the default value. Notably, herbaceous crop pathways are more sensitive to SOC relative to biomass carbon, while the short rotation poplar pathway is the opposite. In the sensitivity scenarios, where parameters were tested independently, the ILUC emission results for these pathways remain negative.

5.4. Emissions from unused cropland reversion

Unused or abandoned cropland could play a critical role in supplying land for biofuels feedstock production, while reverting unused cropland may also lead to changes in soil or vegetation carbon. The default assumption is that the emission factors for converting unused cropland are the same as those for converting cropland pasture. Fig. S7 shows the results from alternative scenarios assuming two lower emissions factors for unused land: 50% of cropland pasture emission factor and zero unused land emissions. Considering emissions from converting unused cropland (the default scenario) moderately increases the ILUC emission intensity for all pathways compared to scenarios with lower (+0.3 to 2.4 g CO_2e MJ^{-1}) or zero (+0.6 to 4.7 g CO_2e MJ^{-1}) unused land emissions factors. Results from the Brazil and EU pathways tend to be more sensitive to the unused land emission factor, given the relatively higher assigned unused land shares in these pathways.

5.5. Shock size and amortization periods

In addition to the shocks developed based on an aggressive future scenario (IEA 450) used in the default scenarios, we investigate its sensitivity by testing a minimal shock size. Fig. S8 compares ILUC emission values from a shock of 6.1 PJ or 50 million gasoline gallon equivalent (MGGE)[7] with those from the default scenario for 11 pathways. These results show lower ILUC emission intensities (e.g., −0.7 to −7.8 g CO_2e MJ^{-1}) from the small shocks in all pathways, with a relatively smaller magnitude for most pathways compared to the large decrease in shock size. As shock size decreases, both the total land use change emissions (numerator) and energy output (denominator) decrease, so the emission intensity does not change dramatically. For the example of corn ATJ in the USA, total ILUC emissions are reduced by about 95% (from 58 to 2.9 $MtCO_2$) when the shock size decreases by about 94% from 104 PJ to 6.1 PJ. Thus, the ILUC emission intensity for this pathway decreases from 22.5 to 21.2 g CO_2e MJ^{-1}. The nonlinearity of ILUC emissions relative to shock size is mainly driven by the extensive margin responses, e.g., the average crop yield could be lower with larger shocks as relatively more newly converted cropland of lower productivity is used.

The choice of the amortization period, a decision usually made by policymakers, directly affects ILUC emission intensity accounting. The impact is nonlinear because the same period is used in accounting for foregone sequestration and peat oxidation. Most USA literature

[7] 50 MGGE is about the capacity of one second-generation biofuels plant usually used in techno-economic analysis, e.g., Zhao et al. (2015).

uses 30-year amortization, while most EU studies used 20-year amortization. Thus, we also report results with 20-year and 30-year amortization periods (see Table S5). The 30-year ILUC emission values estimated for the USA corn ATJ and USA soy oil HEFA are 19 and 18 g CO_2e MJ^{-1}, respectively. In contrast, the value reported in Taheripour et al. (2017c) for the USA corn ethanol and soy biodiesels are 12 and 18 g CO_2e MJ^{-1}, respectively. The disparity can be explained by differences in technology conversion yield between the road and SAF pathways and updates made in this study. For the USA corn pathways, ATJ has a lower yield than ethanol (7.2 vs. 8.7 GJ/t), and unused land emissions (about 2 g CO_2e MJ^{-1}) are considered in our study. The results would be very close if these factors were reconciled. Similarly, for the USA soy oil pathways, the HEFA yield is higher than FAME (fatty acid methyl ester) biodiesel (37.8 vs. 36.6 GJ/t), and unused land emissions (about 1.2 g CO_2e MJ^{-1}) and updates on palm related emission factors also play a role.

5.6. Full life-cycle emissions

The full life-cycle emission intensities, namely the sum of ILUC and CLCA values, are presented in Fig. 6 for SAF pathways. The core life-cycle emission intensities for SAF pathways were estimated by the CLCA group of the Alternative Fuels Task Force (AFTF) and Fuels Task Group (FTG) of ICAO (ICAO, 2020). Across the 17 pathways, the standard deviation is larger for ILUC than CLCA (25 vs. 18 g CO_2e MJ^{-1}), while CLCA has a larger mean value (35 vs. 2 g CO_2e MJ^{-1}). CLCA and ILUC values are positively correlated (with a correlation coefficient of 0.43) since higher yields of crops and technology conversion tend to lower both values. The feedstock is the most important factor explaining variations across the pathways for full LCA emission values. The full LCA emission intensity results indicate that two pathways, corn ATJ in the USA and palm oil HEFA in Malaysia & Indonesia, had an emission intensity higher than the value for petroleum-based jet fuels (89 g CO_2e MJ^{-1}). Cellulosic pathways, driven by the sequestrations in ILUC, had smaller total emission values than other pathways. The two miscanthus pathways result in negative full LCA emissions. Also, SAF produced from sugar crops tend to have lower LCA emission intensity than vegetable oil or starch pathways. These results demonstrate SAFs could play a critical role in mitigating emissions from the aviation sector.

6. Conclusions

In this paper, we extend the existing literature to estimate the induced land use change (ILUC) emissions for seventeen sustainable aviation fuels (SAFs) pathways using a well-established computable general equilibrium (CGE) model, GTAP-BIO, and its coupled emission accounting model, AEZ-EF. The pathways include biomass-based SAFs produced from five ASTM approved technologies, i.e., Hydrotreated Esters of Fatty Acids (HEFA), Fischer-Tropsch (FT), Synthesized Iso-Paraffins (SIP), Alcohol (isobutanol)-To-Jet (ATJ), and Alcohol (ethanol)-To-Jet (ETJ), in four regions, i.e., the USA, EU, Brazil, and an aggregated region of Malaysia & Indonesia. To our knowledge, this is the first study to systematically evaluate ILUC emissions for SAF pathways.

The estimated ILUC emission intensities across the assessed pathways, using a 25-year amortization period, ranged from −58.5 g CO_2e MJ^{-1} for USA miscanthus ATJ to 34.6 g CO_2e MJ^{-1} for Malaysia & Indonesia palm oil HEFA. Comparing across pathways, we find that feedstock is the most critical driver of the variation in ILUC emission intensities relative to technology and region. The four vegetable oil pathways studied have relatively higher ILUC emissions, ranging from 20 (USA corn ATJ) to 34.6 (Malaysia & Indonesia palm oil HEFA) g CO_2e MJ^{-1}, mainly due to their linkage to palm expansion and peatland oxidation in Southeast Asia. All seven cellulosic pathways studied resulted in negative ILUC emissions, ranging from −9.3 (EU miscanthus FT) to −58.5 (USA miscanthus ATJ) g CO_2e MJ^{-1}, mainly driven by the high carbon sequestrations in crop biomass and soil. The ILUC emission intensity for the six starch & sugar pathways ranged from 7.4 (Brazil sugarcane ATJ) to 24.9 (USA corn ETJ) g CO_2e MJ^{-1}. After considering these ILUC emissions in the full life-cycle analysis, fifteen SAF pathways studied resulted in a lower life-cycle emission intensity than petroleum-based jet fuels (89 g CO_2e MJ^{-1}), offering promising options to reduce aviation emissions significantly.

In general, the estimated ILUC emissions for SAFs are consistent with previous estimates for road biofuels from GTAP-BIO and AEZ-EF. The uncertainty of assumptions and parameters used in our modeling, related to, for example, key market-mediated responses, palm related parameters, cellulosic crop yield and related emission factors, and unused land emissions, are communicated with sensitivity tests. This study characterizes work developed to advise the Alternative Fuels Task

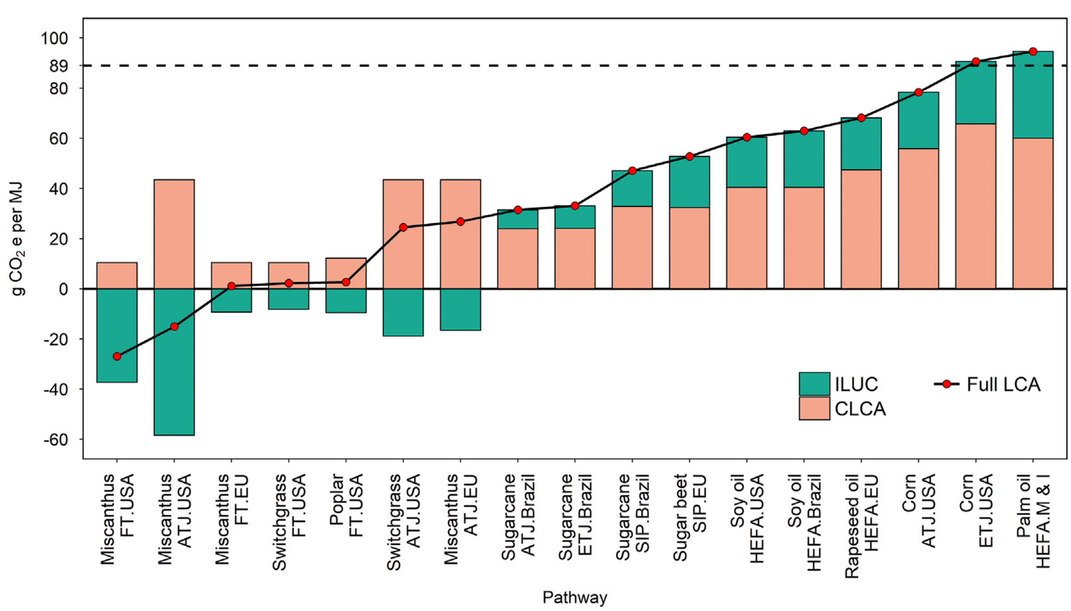

Fig. 6. Full life-cycle emission intensity for sustainable aviation fuels. Bars indicate the composition of the emission intensity (ILUC or CLCA) for a pathway. Points and solid line represent the full life-cycle emission intensity (sum of ILUC and CLCA values). Dotted line shows life-cycle emission intensity of petroleum-based jet fuels. Note that “M & I” represents Malaysia and Indonesia.

Force (AFTF) and Fuels Task Group (FTG) of ICAO. Future study of model intercomparison, i.e., ongoing work to compare results to a partial-equilibrium model, GLOBIOM (Valin et al., 2015b), in the FTG, could further help address uncertainties around data and model design with further harmonized assumptions.

The major contribution of this study is threefold. First, the study introduced SAF pathways into an integrated modeling framework using the latest data to estimate ILUC emissions for SAFs. The framework, including shock size development, coupled modeling between GTAP-BIO and AEZ-EF, and emission intensity accounting, can be used for evaluating new SAF pathways. Second, the study developed a method of land use and emission decomposition to consistently compare SAF pathways. The comparison of seventeen pathways highlighted the critical drivers of ILUC emissions, which provided important management and policy implications. Third, the quantified ILUC emission intensity for SAF pathways from this study contributed to the implementation of the ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), aiming to mitigate global aviation emissions.

CRediT authorship contribution statement

Xin Zhao: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization. **Farzad Taheripour:** Software, Conceptualization, Methodology, Software, Writing – review & editing, Supervision. **Robert Malina:** Investigation, Writing – review & editing. **Mark D. Staples:** Investigation, Writing – review & editing. **Wallace E. Tyner:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.146238.

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16. Abstract

Sustainable aviation fuels (SAFs) are expected to play an essential role in achieving the aviation industries' goal of carbon-neutral growth. However, producing biomass-based SAFs may induce changes in global land use and the associated carbon stock. The induced land use change (ILUC) emissions, as a part of the full life-cycle emissions for SAF pathways, will affect whether and to what extent SAFs reduce emissions compared with petroleum-based jet fuels. Here, we estimate the ILUC emission intensity for seventeen SAF pathways considered by the International Civil Aviation Organization (ICAO), covering five ASTM-certified technologies, nine biomass-based feedstocks, and four geographical regions. We introduce the SAF pathways into a well-established computable general equilibrium (CGE) model, GTAP-BIO, and its coupled emission accounting model, AEZ-EF, to study economy-wide implications of SAF production and estimate ILUC emissions intensity for each pathway. The estimated SAF ILUC emission intensities, using a 25-year amortization period, range from −58.5 g CO2e MJ−1 for the USA miscanthus alcohol (isobutanol)-to-jet (ATJ) pathway to 34.6 g CO2e MJ−1 for the Malaysia & Indonesia palm oil Hydrotreated Esters of Fatty Acids (HEFA) pathway. Notably, the vegetable oil pathways tend to have higher ILUC emission intensities due to their linkage to palm expansion and peatland oxidation in Southeast Asia. The cellulosic pathways studied provide negative ILUC emissions, mainly driven by the high carbon sequestrations in crop biomass and soil. Using the core life-cycle emissions established by ICAO, we show that fifteen of the assessed pathways have a lower full life-cycle emission intensity than petroleum-based jet fuels (89 g CO2e MJ−1), offering promising options to reduce aviation emissions.

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