WORKING PAPER 2020-22

OCTOBER 2020

A comparison of methodologies for estimating displacement emissions from waste, residue, and by-product biofuel feedstocks

Authors: Nikita Pavlenko and Stephanie Searle

Keywords: advanced biofuels, feedstocks, displacement analysis, greenhouse gas emissions, consequential life-cycle assessment

Introduction

Over the past decade, policymakers have grappled with the implications of using food commodities for biofuels. As the body of literature demonstrating the greenhouse gas (GHG) emissions impacts of indirect land use change from first-generation, food-based fuels has grown, interest has shifted toward advanced biofuels made from by-products, wastes, and residues. There is a general expectation that such advanced fuels are likely to have lower climate impacts than most purpose-grown feedstocks, because upstream emissions from these materials' production processes are either not extant or not attributable to these products in typical life-cycle assessment (LCA) methodologies.

However, just as the diversion of food away from existing markets has an effect on land use, the diversion of some common by-products, wastes, and residues away from existing uses may also have unintended consequences. Used cooking oil and tallow, for example, have quickly grown to be among of the largest sources of credits within California's Low-Carbon Fuel Standard (LCFS); this is based on the assessment that they offer greater carbon reductions than vegetable oil-based fuels (California Air Resources Board [CARB], 2019). While these materials are certainly not purpose-grown like vegetable oils, in the absence of biofuels policies, they might have had valuable market uses in sectors like animal feed and oleochemicals. These types of market effects fall outside the scope of direct production system boundaries for LCAs, and the processes and materials involved may not be captured in assessments that use the large-resolution economic models typically used to assess land use change from crop-derived biofuels.

Acknowledgments: This work was generously funded by the David and Lucile Packard Foundation and the Norwegian Agency for Development Cooperation. Thanks to Chelsea Baldino and Jane O'Malley of ICCT, and Chris Malins of Cerulogy, for helpful reviews.

www.theicct.org

communications@theicct.org

twitter @theicct

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

A displacement analysis can improve our understanding of the climate implications of diverting these materials to biofuel production and can be used to identify high- and low-risk feedstocks. A displacement analysis is a type of consequential LCA. While attributional LCA evaluates the average environmental impact of producing one functional unit, a consequential LCA instead assesses the net impacts attributable to changes in behavior. A consequential LCA is more suitable for assessing the net impact of a new policy or a policy change. For example, to answer the question, "What is the environmental impact of my chocolate bar?" it would be appropriate to use an attributional assessment that estimates the GHG emissions along the supply chain of that bar. Because no larger, systemic change is taking place, and the chocolate supply chain remains the same, a historical analysis of that supply chain will accurately reflect the impact of continuing to eat the same kind of chocolate. If the question is instead, "What will be the impact of doubling my country's chocolate consumption?" then substantial changes will be made to the global chocolate supply chain that will change the GHG emissions of the industry. In this case, a historical analysis will not accurately reflect the impact of the market change. A consequential analysis is necessary to assess the change in the global chocolate supply chain and examine the GHG emissions of the new scenario of double chocolate for that country.

In the case of biofuels policy, the question is almost always in the same category as the double-chocolate scenario, as regulators need to assess the GHG impacts of a substantial, policy-driven change to biofuel consumption. Indeed, whether and how displacement GHG emissions are assessed for by-product, waste, and residue biofuel feedstocks has important implications for low-carbon fuel policies. For example, California's LCFS awards credits in proportion to the estimated GHG savings of a biofuel pathway (CARB, 2020). An increase or decrease in the estimated GHG intensity for a biofuel pathway using by-products, wastes, or residues would thus influence the policy signal for that pathway.

Other than a few examples of accounting for reduced methane emissions from municipal solid waste (MSW) and manure, the only low-carbon fuel policy that has accounted for displacement impacts for a by-product, waste, or residue is the United States (U.S.) Renewable Fuel Standard (RFS). The RFS includes displacement emissions in the GHG score for the distillers sorghum oil biofuel pathway that was finalized in 2018, even though displacement emissions are not counted in the GHG scores of other similar feedstock pathways (Renewable Fuel Standard Program: Grain Sorghum Oil Pathway, 2018). In 2017, the European Parliament considered an amendment that would have included accounting for the displacement emissions of by-products, wastes, and residues used in biofuel in the recast Renewable Energy Directive (REDII), and this was based on a previous ICCT study (Searle, Pavlenko, El Takriti, & Bitnere, 2017). However, this amendment was not part of the final directive that passed (European Parliament, 2017).

Given these recent developments, policymakers in the United States and other jurisdictions may be interested in assessing displacement emissions for biofuels produced from by-product, waste, and residue feedstocks in the future. While there have been several attempts to establish a methodology for displacement analysis, and several production systems have been characterized, there is still no consensus on how to include displacement within policy in a consistent way. Here, we seek to support a better understanding of the implications of the methodological choices involved and to help analysts more appropriately match the scope of their LCAs to the questions being analyzed. This paper does not estimate displacement emissions for any particular feedstock or context. It instead highlights several key methodological considerations available to policymakers and illustrates their potential impacts on the results.

Literature review of approaches to displacement analysis

Displacement effects occur when biofuel policies incentivize the diversion of a feedstock away from its existing uses and that feedstock needs to be replaced by substitutes. While the impact of using commodity food crops for biofuels and diverting them from their existing uses is typically assessed using indirect land use change (ILUC) accounting, there is no consensus about how to estimate the impact of these displacement effects for non-food biofuel feedstocks. Nonetheless, there are several examples of displacement analysis in the literature, including proposed methodologies for identifying and quantifying these effects, and estimates of displacement emissions for several biofuel feedstocks.

Conceptually, estimating displacement emissions is similar to the "system expansion" approach for LCA, in which allocation, or the separating out of total attributable emissions from a product system and dividing them among a set of co-products, is replaced by estimating the avoided emissions from the reduced production of the materials that those co-products replace on the market (Brander & Wylie, 2011). System expansion is generally used to credit an avoided burden to a primary product for cases in which a co-product replaces a material in a separate market. For example, system expansion can be utilized for some biofuel pathways that export excess electricity as a co-product because it allows for crediting the product system for the avoided fossil electricity displaced from the grid. A displacement analysis considers the opposite case in which the product of interest has an existing use and its diversion creates a new burden that is attributed to the primary product's new use. In order to estimate the new burden attributable to the product, it is necessary to (1) identify the existing uses for that material and the expected behavior in response to its diversion; and (2) develop a systematic approach for translating that expected behavior into a quantified environmental impact.

Some studies apply different LCA boundaries or analytical scopes depending on the categorization of the feedstock. For example, a waste from a product system will be assessed differently than a co-product. However, there are no universal definitions of product categories and the distinctions between some categories may be flexible. For displacement analysis, the literature is inconsistent on whether feedstock categorization is necessary. In an effort to develop a more systematic method of assessing the life-cycle emissions of various biofuel feedstocks, ICF International (2015) developed a categorization approach for classifying biofuel feedstocks and assessing their emissions. That study classified feedstocks on the basis of their economic value and the elasticity of their supply. "Primary" products were defined as the intended, high-value products of a production process with elastic supply. In contrast, by-products have some economic value, but their supply was considered inelastic to their price. Lastly, wastes and residues were defined as low-value products and products for which supply is inelastic to price. Given that markets for by-products, wastes, and residues are generally difficult to characterize using ILUC models, ICF recommended a simplified displacement approach that acknowledges that these materials may have existing uses and that discontinuing those uses could lead to indirect emissions. While other analyses and methodologies draw a distinction between by-products, wastes, and residues, the case studies assessed by ICF International (2015) suggested that if they have existing uses, a displacement approach is needed regardless of their material category.

One of the earliest attempts to characterize displacement emissions was prompted by the U.K. Department for Transport when it commissioned a study to investigate the risk that the Renewable Transport Fuel Obligation (RTFO) would generate adverse effects by diverting tallow away from its existing uses. The authors found that biodiesel demand could raise the price of tallow and that its diversion may result in greater use of more GHG-intensive replacements (Reece et al., 2008). Those findings then prompted further analysis by Reece et al. (2008) in a proposal for the U.K. Renewable Fuel Agency's (RFA) consultation on the RTFO. That study proposed a three-step approach for estimating displacement emissions from potential feedstocks and drew a distinction between waste materials and by-products that have existing productive uses.

Brander et al. (2009) provided a detailed proposal for a methodology for estimating displacement effects for by-products, wastes, and residues for the U.K. RFA within the context of the Renewable Energy Directive (RED); this study was an attempt to expand the analysis for tallow conducted by Reece et al. (2008) to a wider set of feedstocks. Brander et al. (2009) assessed four case studies for materials with potential displacement emissions, including MSW, inedible tallow, wheat straw, and molasses. For each feedstock, the authors illustrated the well-to-wheel (WtW) emissions attributable to biofuel made from each material and performed a sensitivity analysis using a range of displacement assumptions. The authors highlighted that while the uncertainty around displacement emissions is high, in cases where there is a consistent directional result, policymakers may be able to draw clear conclusions. For example, it would be potentially risky for a policy to treat displacement emissions for a given feedstock as zero due to uncertainty if the range of results from the displacement analysis was both positive and large relative to the direct emissions.

Peters and Stojcheva (2017) developed a detailed market assessment for crude tall oil (CTO). The authors assessed the total global potential for CTO production relative to existing levels, while noting that additional production may be possible through deployment of acidulation equipment at existing pulp mills. The authors then evaluated the market for CTO by examining the demand for non-biofuel uses and the products that could substitute for CTO and its final distilled products in those markets. While the authors did not explicitly estimate displacement emissions for CTO diversion from other uses, they assessed CTO's existing uses and described the potential market impacts from increased diversion. The study concluded that CTO is a process residue rather than a primary product of pulp mills for the process of categorization under the EU RED. This conclusion is primarily based on the finding that CTO production is semi-elastic and that greater quantities can be produced via acidulation. However, the analysis did not take into account the second-order impacts on displacement caused by increased production of CTO from other pulping residues with their own existing uses.

In the aforementioned study referenced by the European Parliament in its draft amendments to the REDII, Searle et al. (2017) assessed the displacement emissions for a selection of potential biofuel feedstocks in the EU context and the fuels' total LCA emissions with indirect displacement emissions included. The study found that some feedstocks' displacement emissions reduced biofuels' GHG savings to zero compared to the fossil fuel comparator. In particular, feedstocks with existing uses that necessitate substitution from fossil energy or palm oil had the highest emissions in the analysis.

In its 2018 rulemaking on distillers sorghum oil, the U.S. Environmental Protection Agency (EPA) noted that removing sorghum oil from distillers grains with solubles (DGS) that are intended for animal feed changes the caloric energy and nutritional content of the DGS. EPA therefore estimated the feed substitution ratio for corn, in pounds of corn per pound of oil extracted, to displace the quantity of sorghum oil diverted to biofuel production from DGS used for livestock feed. As some livestock respond differently to the removal of oil from their feed than others, EPA calculated the displacement ratios for several different types of livestock. After conducting this displacement analysis, EPA then added the emissions from corn substitution to the direct LCA emissions for producing sorghum oil biodiesel in order to assess the GHG performance of this pathway.

Additionally, for several waste materials associated with methane emissions from anaerobic decomposition, such as MSW-derived diesel and livestock manure-derived biogas, displacement emissions have already been incorporated into fuels policies. These feedstocks, which decompose and generate methane if otherwise unused, are credited for the quantity of avoided methane emissions. CARB utilizes a displacement approach to credit fuels from both of these pathways on the basis of their upstream avoided methane emissions within the California Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model used for the LCFS (CARB, 2019). Moreover, a life-cycle assessment of several aviation biofuel pathways developed by the European Commission's Joint-Research Centre (JRC) identified displacement emissions from feedstock diversion as a critical area for further research prior to the scaling up of that industry (O'Connell, Kousoulidou, Lonza, & Weindorf, 2019).

Overall, there is an emerging recognition that indirect emissions from displacement are important to understanding the overall GHG impacts of deploying fuels made from by-products, wastes, and residues. However, because there is not a clear and consistent methodological approach for assessing those indirect emissions, their contribution to alternative fuels' overall emissions remains highly uncertain.

Steps for assessing displacement effects

Displacement analyses in the literature generally build on two different methodologies. The first, developed by Reece et al. (2008), is a three-step process for identifying existing processes affected by feedstock diversion and then attributing the displacement impacts to biofuel production. This approach was expanded upon by Brander et al. (2009), which developed a series of case studies for different materials and documented the assumptions necessary at each stage of the analysis. Here, we draw upon Brander et al. (2009) to describe the sequence of steps necessary to conduct a displacement analysis.

Each step of the displacement methodology is summarized below, in chronological order:

1. **Define the material.** While this step might sound as if it should be simple, the precision and clarity of the material definition of the feedstock may greatly affect the scope and rigor of the analysis in the following steps.
2. **Estimate the quantity used for bioenergy.** This estimate of the quantity of the material to be used for new biofuel or bioenergy production will inform assessment of the extent to which the diversion will cause displacement effects.
3. **Develop an inventory of existing uses.** Evaluate the feedstock's existing uses within the scope of the material definition above, describing those existing uses and the quantity of the material used in each.
4. **Develop an inventory of material substitutes or alternative production systems.** For each existing use assessed above, determine either the substitute material used when the feedstock is diverted, or the change in production practices to supply the displaced service. Depending on the existing use in question, this stage of the analysis may involve developing a substitution ratio or assessing demand reduction in response to feedstock diversion. Finally, a cost estimate for

each alternative material or production system must be developed in order to assess the most likely market response to feedstock diversion.

5. **Evaluate the "order of dispatch" in which substitutes or alternative production systems replace the diverted feedstock material.** Based on the inventory of material substitutes and alternative production systems developed in step 4, develop an estimate of the expected order in which these alternatives replace the displaced feedstock. This estimate should be based off of the costs and technical constraints identified in step 4. Brander et al. (2009) recommended that if there is insufficient data to create this order of dispatch, a weighted average displacement based on existing uses should be estimated instead.
6. **Calculate the quantity of each substitute material or alternative production system used.** Based on the quantity of feedstock demand from step 2 and the inventory of existing uses developed in steps 4 and 5, estimate the quantity of substitute materials and alternative production systems necessary to compensate for the diverted material.
7. **Calculate the change in emissions attributable to the use of each substitute material or alternative production system.** For each identified substitute material or alternative production system necessary due to feedstock diversion, estimate the life-cycle emissions attributable to that material or system.
8. **Attribute the displacement emissions to the functional unit of delivered bioenergy.** Take the per-unit emissions for substitute materials and production systems and scale them according to the overall quantity of feedstock diverted to bioenergy.
9. **Calculate displacement emissions per unit of delivered bioenergy.** Take the total displacement emissions estimated in step 8 and divide by the quantity of feedstock diverted to bioenergy production from step 2, normalizing the results in terms of emissions per unit of bioenergy.
10. **Conduct a sensitivity analysis for steps 1–7.** Develop a sensitivity analysis for steps 1 through 7 by identifying the key parameters and assumptions in the displacement analysis and testing their impact on the final result.

While Brander et al. (2009) provided a methodological basis for assessing displacement effects and quantifying displacement emissions, there remains substantial methodological flexibility within the framework for evaluating a given feedstock. In addition, not all of the steps above must necessarily be completed if the analyst adjusts the methodology. In the following sections, we assess how various methodological choices within the steps could impact the indirect emissions estimated for a given feedstock using several illustrative examples. We largely draw upon the displacement methodology developed in Brander et al. (2009), but also incorporate elements of more recent studies that utilized variations of this 10-step approach.

Defining a material and establishing a scope of analysis

Establishing the scope and defining the feedstock for a given displacement analysis can greatly impact the later stages of the analysis. It is necessary to define not only a feedstock's category, but also the geographic and temporal scope for the assessment.

The process of categorizing a feedstock is one of distinguishing between primary products, co-products, by-products, wastes, and residues (ICF International, 2015). The supply of primary and co-products is expected to be relatively elastic to price, whereas the supply of other materials is relatively inelastic. ICF International (2015) recommended assessing primary and co-products using attributional LCA, allocating the production emissions across co-products, and then assessing ILUC emissions for those primary or co-products grown on cropland. In this case, the ILUC emissions could be considered the displacement emissions for primary products in those analyses. In practice, though, there is often a gray area between by-products and co-products. Depending on the scenario, the relative value of a co-product may be insufficient to justify increasing production of the total product system in response to demand. This would instead necessitate substitution for that co-product on its own. For example, Santeramo and Searle (2018) found that while soybean production is relatively inelastic to the soy oil price in the United States, there is a large response from palm oil imports to changes in soy oil price; this indicates that the dominant response to diverting soy oil to biofuel production is substitution with palm oil in non-biofuel uses. In cases like these, economic modeling may be necessary to assess the degree to which the demand shock generates both substitution and demand for additional production.

For non-primary products, standard LCA practices distinguish by-products that have relatively significant economic value from wastes and residues. A share of upstream processing emissions for the product system can be allocated to by-products according to their energy content, mass, or economic value, depending on the methodological choices made in a given study (ICF International, 2015). In contrast, for wastes and residues it is common practice to exclude upstream extraction and production emissions, with emissions calculated from the point at which the material is separated out from the production process in which it was generated through to final use for energy (GREET, 2018; Edwards et al., 2014). It is necessary to distinguish between by-products and wastes and residues if the analyst decides to include allocated upstream emissions for by-products but not for wastes and residues. Additionally, if materials have existing uses, a displacement analysis may be necessary regardless of their categorization and whether their upstream emissions are treated.

Assumptions about geographic scope could greatly impact our understanding of the displacement impacts of some feedstocks, because the existing uses for a given feedstock may vary considerably from region to region. Furthermore, some feedstocks may be more easily transported than others, meaning that some feedstocks may be imported to meet one jurisdiction's bioenergy demand, whereas other feedstocks are more likely to stay close to where they are produced. Explicitly defining a given feedstock's region of origin as part of its definition thereby establishes a geographic scope for the analysis and determines the counterfactual scenarios for feedstock diversion.

To illustrate the impact of geographic scope on displacement emissions, we first evaluate the case of used cooking oil (UCO) used for biofuels. UCO is primarily discarded in the European Union, whereas in the United States, recovered UCO has historically been used for animal feed (EPA, 2014). Given the lost nutritional content in the feed, the displaced UCO would need to be replaced with its lowest-cost substitute. In its rulemaking on LCA emissions from sorghum grain oil-derived biofuel, EPA noted that the quantity of oils removed from livestock feed is likely not sufficient to cause farmers to deliberately replace sorghum oil with other oils, for example by increasing the ratio of whole oilseeds to oilseed meal; therefore, EPA assumed the nutritional deficit would primarily be met with additional corn (Renewable Fuel Standard Program: Grain Sorghum Oil Pathway, 2018). An analysis of historical changes in livestock feed composition in response to changes in distillers corn oil production supported this assumption (Searle, 2019). In its RFS regulatory impact analysis, EPA estimated the GHG emissions impact of corn cultivation as 0.58 kilograms (kg) of carbon dioxide-equivalent (CO_2e) for each kg corn.[1] If we assume that corn grain substitutes for UCO at a ratio of 1.2 kg of grain per 1 kg of UCO diverted, as EPA does for sorghum oil, we estimate displacement emissions of approximately 0.70 kgCO2e per 1 kg of diverted UCO.

Figure 1 illustrates the relative life-cycle emissions for UCO biodiesel using three separate definitions of geographic scope. While in this case we compare EU to U.S. UCO emissions, for the remainder of the paper we focus on U.S. examples. The first example is UCO produced in the United States, and in the second it is produced in the European Union. For each case, we show the direct emissions from producing UCO biodiesel, taken from California-GREET. Assuming a yield of 0.8 kg of biodiesel per 1 kg of UCO processed, we then attribute indirect displacement emissions to the biodiesel depending on the portion that has been diverted from animal feed. In the U.S. case, we fully attribute emissions from displaced animal feed to the biodiesel, and this results in an additional 23.4 gCO_2e per megajoule (MJ) of emissions. If we define our UCO as only that discarded in the European Union, the displacement emissions are zero, because UCO has been banned from use in animal feed since 2004 (Pelkmans et al., 2014).

If we expand the definition of EU UCO biodiesel to include not only that made from UCO generated within the European Union, but also the quantity imported from the United States, the displacement emissions should take into account the fraction of UCO that is diverted from livestock feed in the United States. In this case, we attribute displacement emissions from animal feed from the U.S. share of imported UCO in the EU case, which is approximately 11% of EU UCO consumption (Baldino, Searle, & Zhou, 2020; U.S. Department of Agriculture, 2019). Using that expanded scope, the displacement emissions for EU UCO biodiesel rise to 2.6 gCO_2e/MJ.

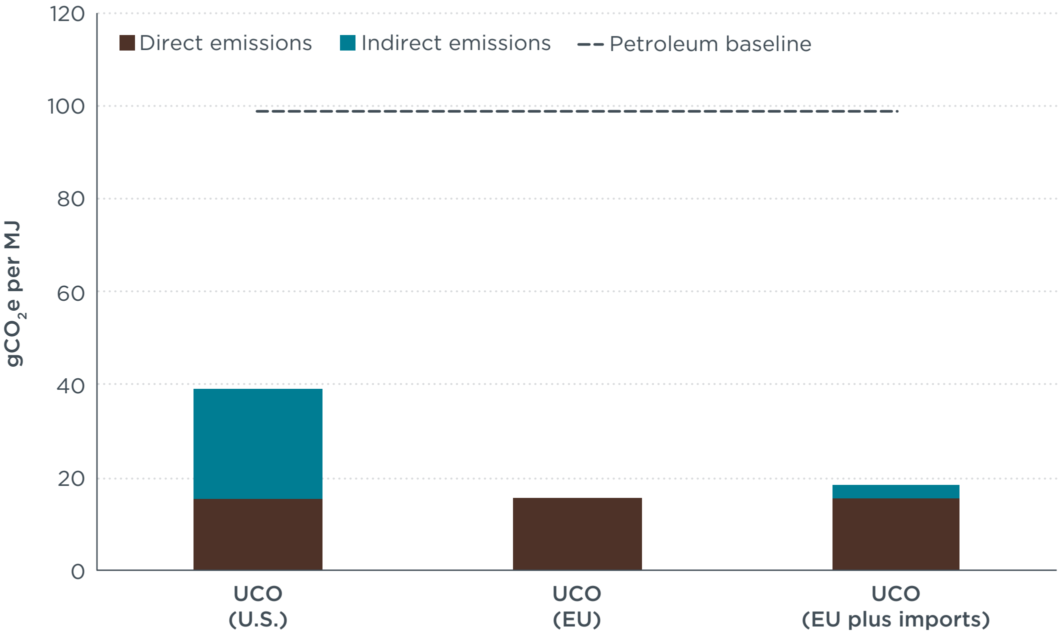

Figure 1. Comparison of indirect displacement emissions for UCO biodiesel across three geographic scopes. Source: California-GREET Tier 1 default value for UCO biodiesel, less than 500 miles transport by truck

---

[1] Value taken from Renewable Fuel Standard Docket: EPA-HQ-OAR-2017-0655-0090, Distillers' Sorghum Oil LCA Spreadsheet

As with geographic scope, defining a precise temporal scope for a displacement analysis allows us to more accurately assess the historical existing uses for a material and/or to project future behavior. Displacement effects are not static: Existing uses for materials change over time in response to new policies, technological changes, and economic factors. For example, the 2004 ban on UCO in animal feed in the European Union caused it to be discarded in the absence of biofuel conversion, and this meant displacement emissions of zero. Likewise, the introduction of a similar law in the United States would negate the indirect emissions for UCO diversion discussed earlier.

The most straightforward way to characterize the temporal scope of a material is to look at its most recent historical use. Analysts must balance the time period they have data for with the scope of their analysis. If the data is several years old but there have been no legislative or technological changes since, that data may be suitable for a near-term analysis. The analysis developed by Brander et al. (2009) assembled the inventory of existing uses based on present-day uses but noted in the sensitivity analysis that these factors should be assessed as they change over time. This approach is acceptable in most cases for materials without a large existing biofuel market. However, if a material is already fully utilized for biofuel, a present-day view may understate displacement effects. For example, at present, all but a small fraction of UCO in the United States is either exported or converted into biofuel (Baldino et al., 2020). In this case, a historical analysis prior to the introduction of biofuel incentives may more accurately reflect that material's diversion from livestock feed.

In cases where past behavior is not expected to be a predictor of future trends, it may be necessary to develop a displacement analysis that factors in future expected changes in the market. If the policy that the displacement analysis is intended to inform has a long timeframe, the analysis should be designed to align with expectations of future changes. For example, the introduction of new laws affecting by-products, wastes, and residues or introducing renewable energy mandates in other economic sectors could greatly change our understanding of the displacement impacts for a given material over time. These decisions can be informed at the outset by determining how often the analysis will be revisited for sensitivity analyses. If it is a one-time assessment for a policy, anticipating future changes at the outset, to the extent possible, will lead to greater policy certainty and give a more meaningful result. On the other hand, if the assessment is intended to be revisited every 5 years for a policy, it may not make sense to try to account for future changes at all.

Displacement effects for non-market existing uses

Challenges may arise when considering the existing uses of materials for which there is not an established market value. For example, the increased collection of some agricultural and forestry residues may have soil carbon implications. Where agricultural residues are left on the field after harvest, this practice helps maintain soil health, and stocks of organic carbon and nutrients. An important question in a displacement analysis for these materials is whether leaving them in place constitutes an existing use, and if so, how to account for their diversion. If we exclude existing uses without a monetary value, we imply that use as a soil amendment does not carry any climate implications. Additionally, this assumption would contradict the evidence, at least in some regions, that leaving residues in place has value to farmers. Townsend et al. (2018) found in a survey study that farmers in the United Kingdom were unwilling to sell a certain share of residues absent a high price due to their desire to maintain soil quality and support future yields. This mindset may not be prevalent everywhere, though, and this again highlights the importance of geographic considerations. In situations where the residues are diverted beyond typical levels, it may be desirable to calculate the GHG emissions from soil carbon losses as a result of the excess residue removal and attribute them to the diverted material. That analysis could also capture the indirect impacts such as reduced future crop yields due to lower soil organic carbon stocks. Still, accurately accounting for this effect would be difficult.

In some cases, there may be justification for excluding soil impacts from a displacement analysis. For example, it is possible that policies could limit the removal of residues used for biofuel production in order to protect soil quality. Note, though, that we are not aware of any such policies presently in place. Likewise, one could assume up front that farmers have an incentive to maintain their soil quality or that the estimated quantity of residues utilized because of the policy is too small to drive unsustainable diversion. Brander et al. (2009) noted that modeling soil carbon losses from wheat straw diversion may be prohibitively complex and it is excluded from that study's wheat straw displacement analysis because of the uncertainty; the study only assessed emissions from displacing wheat straw from market uses. Searle at al. (2017) assumed that farmers only remove the sustainably available portion of residues when estimating indirect emissions for wheat straw, and assumed that farmers then divert the remaining portion from other uses such as animal bedding and mushroom cultivation. Searle et al. (2017) estimated displacement emissions of 8 gCO_2e/MJ for wheat straw using these assumptions.

Quantifying the impact of residue diversion and attributing it to biofuel feedstocks can also introduce uncertainty due to substantial geographic and temporal variations. Valin et al. (2015) simulated soil carbon emissions and yield loss using the EPIC model and included the results in an analysis of land use change emissions from a cereal straw shock in the European Union to produce ethanol. As a component of that study's overall analysis of straw diversion, the authors estimated that there are soil carbon losses attributable to the demand shock, and this resulted in a land use emission factor of 16 gCO_2e/MJ. The authors noted that within that emission factor there is substantial regional variation in how farmers are expected to collect residues. This strong regional variation is attributable to that study's assumption of high transport costs for wheat straw that prevent the development of an EU-wide market. Valin et al. (2015) used three countries with varying levels of straw availability as a proxy for the levels of availability in the European Union in response to a 1% supply shock; at one end, Hungary diverts sufficient residues to create a land-use impact of 60gCO2e per MJ because that country already collects more residues than can be sustainably harvested. Meanwhile, farms in France currently collect much less straw than is sustainably available and therefore straw biofuel in that country does not generate soil carbon losses.

Figure 2 illustrates the impact of different assumptions on the displacement emissions for wheat straw ethanol, showing a range of 1 gCO_2e to 16 gCO_2e per MJ. The result for wheat straw in Brander et al. (2009) is on the lower end of the range, as it includes the substitution emissions from displaced animal bedding and fertilizer but omits any estimate of soil carbon losses.[2] While Searle et al. (2017) also omitted soil carbon losses, it estimated higher displacement emissions largely due to the significant amount of wheat straw diversion from heat and power, where it is assumed to be replaced in part by pulpwood with emissions of 144 gCO_2e/MJ; the remaining existing uses yielded a similar result to that of Brander et al. (2009). While Valin et al. (2015) assumed some

---

[2] The widespread worst-case impact scenario for wheat straw in the study generates displacement emissions of 3.12 gCO_2e/MJ

degree of demand reduction in existing uses and a marginal increase in additional land conversion, the primary drivers for emissions from wheat straw diversion were from soil carbon losses and yield reduction. Accounting for soil impacts can thus significantly affect total displacement emissions for crop residues, although the impact likely varies considerably depending on the geographic region assessed.

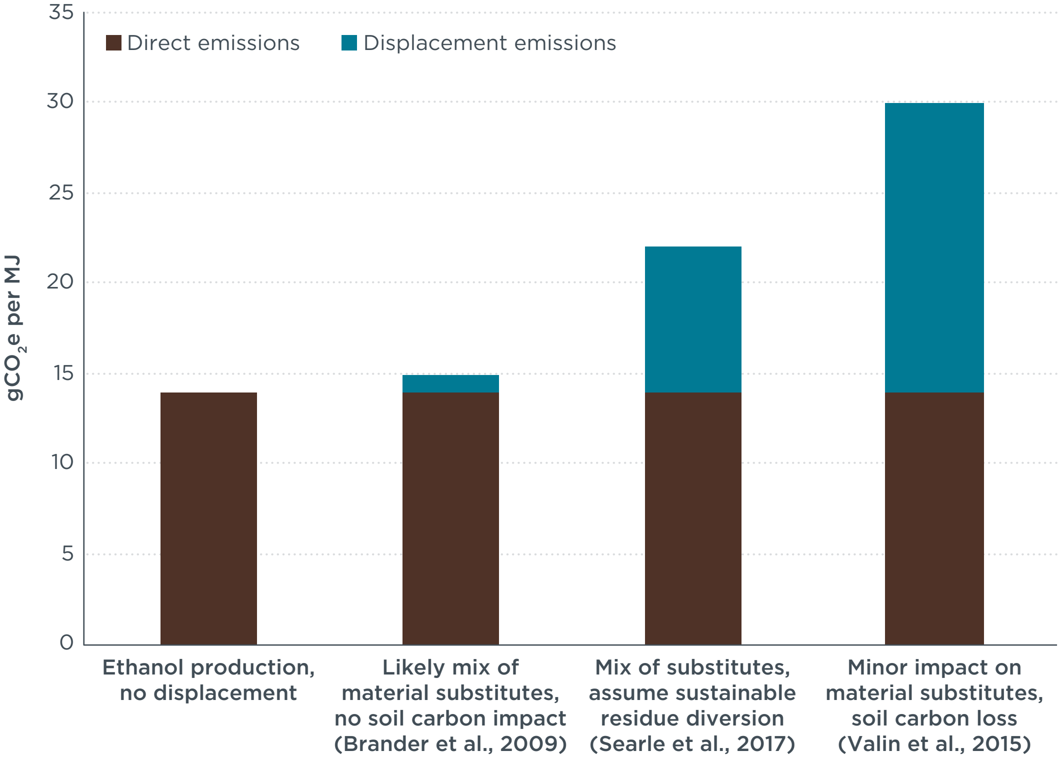

Figure 2. Comparison of displacement emissions for wheat straw and agricultural residue-derived ethanol

Options for resolving multiple existing uses

For materials with a variety of existing uses beyond biofuel, the results of a displacement analysis can be particularly sensitive to assumptions about the uses from which the material is displaced. There is often considerable variation in the GHG impacts of substitutes for different uses.

To illustrate the impact of using different methodologies for assessing the displacement of a biofuel feedstock from a number of other uses, we examine the market for CTO in the United States. CTO is a by-product of the Kraft Process for wood pulping and has several uses. Crude sulphate soaps (CSS) are separated from black liquor and then acidulated to produce CTO. Not all pulping mills generate CTO. Some choose to combust the CSS directly or lack an acidulator. Therefore, there is some flexibility in CTO supply, as there is some unrealized potential in some regions to expand acidulation and utilize a greater portion of their CSS. In this section, we estimate only the impact of diverting CTO from its existing uses, rather than the expansion of total CTO supply through increased acidulation. We primarily utilize an assessment of CTO global supply and demand prepared by Peters and Stojcheva (2017) to evaluate the existing uses for CTO. The authors stated that in the United States, CSS is primarily acidulated offsite at distilleries that also distill the resulting CTO, and those distillation facilities primarily use natural gas as a process fuel. In some cases, though, facilities directly combust CTO or certain distilled products. The supply of CTO within the United States exceeds domestic demand, and a portion of production is exported to the European Union.

As of 2020, total North American production of CTO is estimated to be approximately 900,000 tonnes annually, and there is the potential for additional production through increased acidulation of CSS (Aryan & Kraft, 2020). Assuming an average yield of 30 kg to 50 kg of CTO per tonne of pulp produced and that study's estimate of approximately 39.5 million tonnes of North American softwood pulp production using the Kraft process in 2020, we estimate that the theoretical total CTO production could grow to approximately 1.2 million–1.9 million tonnes of CTO (Aryan & Kraft, 2020). While exact figures on the existing uses for CTO in the United States are not available, Baldino et al. (2020) provided an approximation of the distribution of existing uses for CTO in the U.S. market, and this is illustrated in Figure 3, below. Approximately 61% of CTO in the United States is distilled into a variety of products with varying end uses, such as tall oil pitch, tall oil rosin, and tall oil fatty acids. Smaller shares go toward oil drilling and onsite energy recovery; onsite energy recovery at distilleries is much less common than in the European Union due to the low cost of natural gas. As the supply of CTO in the U.S. market exceeds domestic demand, a substantial share (29%) is exported, predominantly to the European Union.

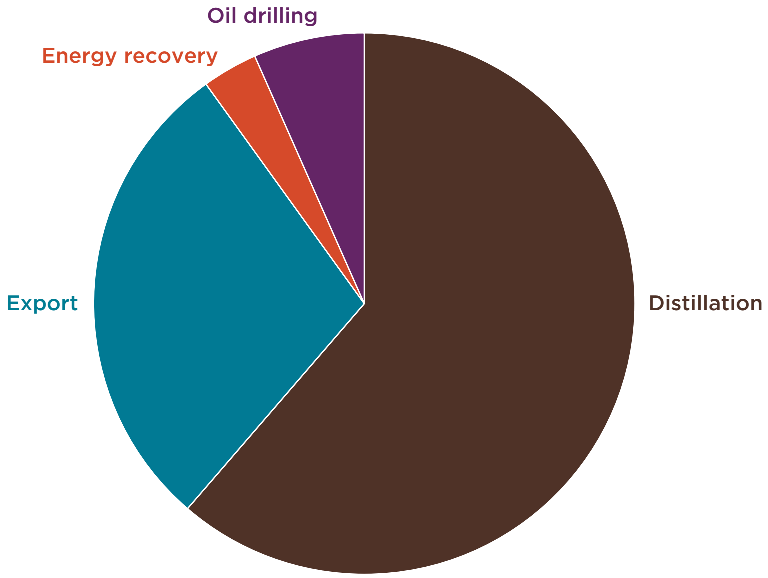

Figure 3. Estimate of existing uses for CTO in the United States, 2017

Of total North American CTO production, roughly 3% is combusted for energy directly. Approximately 16% and 7% of distilled CTO is converted into tall oil pitch and tall oil heads, respectively, and these are both combusted for energy (Peters & Stojcheva, 2017). The remainder of the distilled portion goes toward varied uses as an adhesive, rubber, paint, or surfactant (Cashman et al., 2015). Together, bioenergy accounts for approximately 18% of total CTO use in the United States, including a share of exports. We assume that direct CTO combustion at distilleries is replaced by natural gas. Cashman et al. (2015) assumed that tall oil pitch and tall oil heads are replaced by heavy fuel oil (HFO).

We use this data to illustrate three separate approaches for addressing the displacement of materials with multiple existing end uses, from least complex, average displacement, to most complex, price supply curves. In each case, we utilize emission factors from

Cashman et al. (2015) for material substitutes for distilled CTO derivatives and assume a yield of 0.81 tonnes of renewable diesel per tonne of CTO.

Average displacement

When a by-product, waste, or residue has multiple existing uses, as in the case of CTO, the most straightforward method for assessing displacement emissions is to assume that the material is diverted evenly across its existing uses. In other words, we assume that the likelihood of the diversion from its existing uses is proportional to the amount of material used in each of those uses. This is the baseline approach recommended by Reece et al. (2008); likewise, while Brander et al. (2009) recommended utilizing an order-of-dispatch approach where data is available, the authors ultimately utilized an average displacement method for each of the four case studies in their analysis due to data limitations. Likewise, EPA utilized an average weighted displacement approach in its assessment of the impact of sorghum grain oil diversion from animal feed; the approach assumes that its diversion affects markets in proportion to its consumption. Searle et al. (2017) used an average displacement approach to estimate the emissions attributable to increased CTO demand in the EU context.

For this example, we evaluate the impact of diverting 100,000 tonnes of CTO for renewable diesel production in the U.S. context, and this is similar to the production volume of a commercial renewable diesel bio-refinery (Voegele, 2012). First, we assume exports (260,000 tonnes) to be outside the scope of the analysis and that exports cannot be displaced. This leaves approximately 640,000 tonnes of domestically consumed CTO remaining from the original 900,000 tonne annual North American production estimate.[3] To assess average displacement for CTO, we then break down the end-uses for distilled tall oil from Cashman et al. (2015) and Malins (2017), as illustrated in Figure 4. Based on the inventory of end-uses assessed by Cashman et al. (2015), we assume that CTO that is combusted at acidulators or distilleries for energy recovery in a boiler would be replaced by natural gas, whereas the distillation end products tall oil pitch and tall oil heads would be replaced by HFO. We assume CTO used for oil drilling is displaced by non-combusted petroleum (De Almeida et al., 2016).[4] We assume that material end-uses for distilled CTO in surfactants, adhesives, and rubber would be replaced by soy oil, gum rosin, and C5 hydrocarbon resins bearing life-cycle production emissions as described by Cashman et al. (2015). Using this simplified approach, we estimate that the displacement emissions for CTO are approximately 53 gCO_2e per MJ.

---

[3] Treatment of exports is discussed separately in this paper; for the purposes of this section, we strictly consider domestic CTO displacement.

[4] For emissions attributable to non-combusted petroleum, we estimate upstream emissions attributable to domestic U.S. light crude oil. See Appendix for more details.

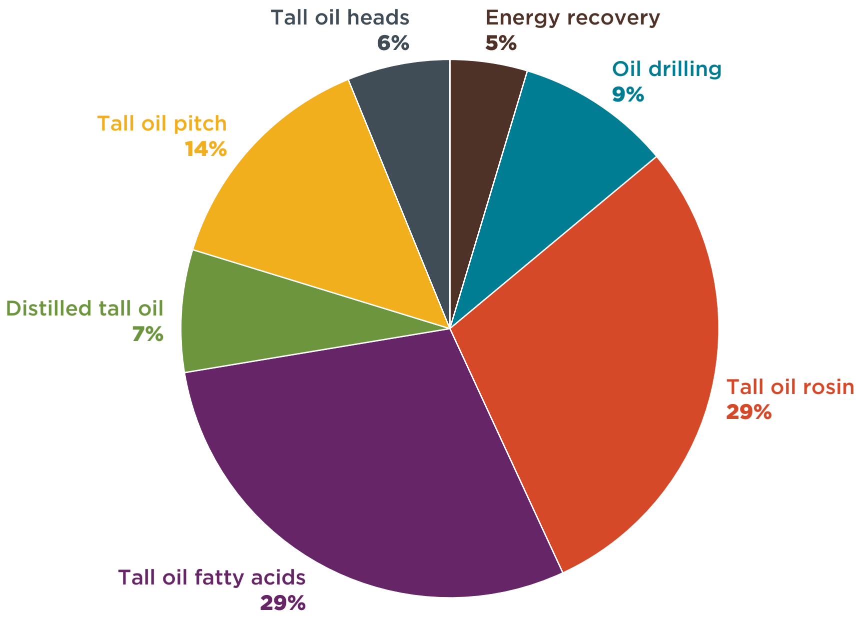

Figure 4. Relative shares of CTO end uses after accounting for CTO distillation in the U.S. market.
Note: Adapted from Cashman et al. (2015) with further inputs from Malins (2017)

Order of dispatch

An "order of dispatch" approach is an attempt to navigate multiple existing uses by organizing them in the order in which their feedstock would be displaced with increasing demand for that feedstock. In this methodology, which attempts to more closely model real-world changes in behavior, those existing uses with the cheapest alternatives are the first to substitute the feedstock in question with another material; the process then continues for each existing use in increasing order of price until the projected demand for the feedstock is met. This approach is much more data-intensive than the average displacement approach, as it requires the following pieces of information in order to estimate a displacement impact: (1) the quantity of new demand for a given feedstock; (2) the quantity of that feedstock used in each of its existing uses; and (3) the price of the cheapest substitute for that feedstock in those existing uses.

The displacement methodology developed by Brander et al. (2009) recommended building an order of dispatch based on "consideration of price, and technical, consumer preference, or regulatory constraints to substitution" (p. Appendix III, p. 3). Despite that guidance, the authors utilized the average displacement method for each of the four case studies presented in their analysis due to data limitations. Malins (2017) utilized a partial order of dispatch approach to assess the expected distribution for some materials, though data limitations once again prevented a full analysis.

An order of dispatch analysis is more complex because it not only requires full consumption and price data for each of a given material's existing uses, but also requires the expected prices for substitute materials for each of those uses. CTO, for example, has a varied set of end uses after distillation, and thus detailed price data for commodities such as HFO and soy oil, as well as more specialized substitutes in the chemical industry such as resins, is needed. The emissions for substitute materials and production systems can vary widely depending on the existing use, making the final displacement emissions estimate very sensitive to the projected order of dispatch. Here, we utilize the life-cycle emission factors for the production and use of material substitutes for CTO and its distilled end products estimated by Cashman et al. (2015). Figure 5 illustrates the emissions for extracting and manufacturing substitute materials in terms of kg CO_2e per tonne of substitutes; for the energetic uses shown in orange, these emissions include the combustion emissions of those substitutes. Note, too, that the choice of material substitutes may change over time as price and consumption relationships shift. This adds more uncertainty and complexity to the analysis.

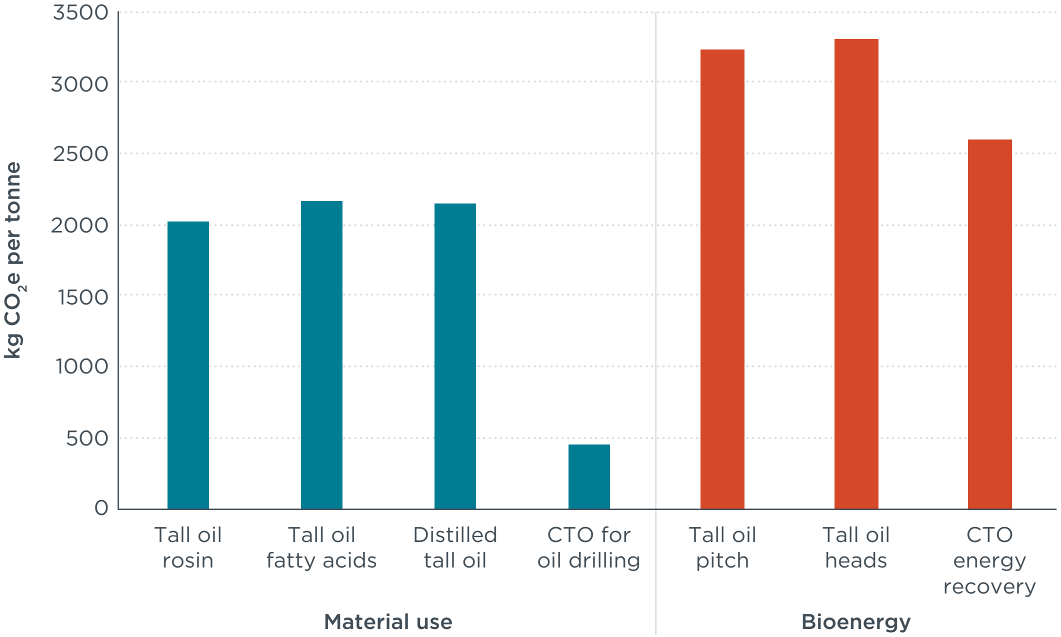

Figure 5. Comparison of substitution emissions for CTO substitutes across end uses.

Note: Weighted average for distillation end products with multiple uses. Source: Adapted from Cashman et al. (2015), and we assume that CTO used for oil drilling is displaced by petroleum crude.

Due to data limitations, below we present a simplified order of dispatch for CTO based on an assumption of increasing complexity of replacement. Here, we assume that onsite combustion of CTO—a relatively small portion of use in the U.S.—is relatively easy to displace through increased combustion of natural gas. This is followed by CTO use in oil drilling, the substitute for which is crude petroleum, depending on oil prices (Peters & Stojcheva, 2017). We assume that the emissions from the use of crude petroleum are low here because the petroleum is not combusted for energy in this use. From there, the next two most likely end uses for which the feedstock would be diverted are combustion of tall oil pitch and tall oil heads, which can instead use HFO (Energy Information Administration [EIA] 2020a; EIA 2020b). Next, we assume that tall oil fatty acids, which can be replaced with soy oil, are the next likeliest existing use to be replaced. Lastly, we assume that distilled tall oil and tall oil rosin, which have the most specialized substitutes, would be the last to be diverted. Figure 6 shows a hypothetical order of dispatch for CTO end uses relative to the quantity of each use in the United States. As the quantity of CTO diverted for biofuel increases on the y-axis, the diversion of materials from existing uses progresses from left to right along the x-axis. For example, as new demand approaches 100,000 tonnes, the first diverted CTO will come from energy recovery, followed by oil drilling.

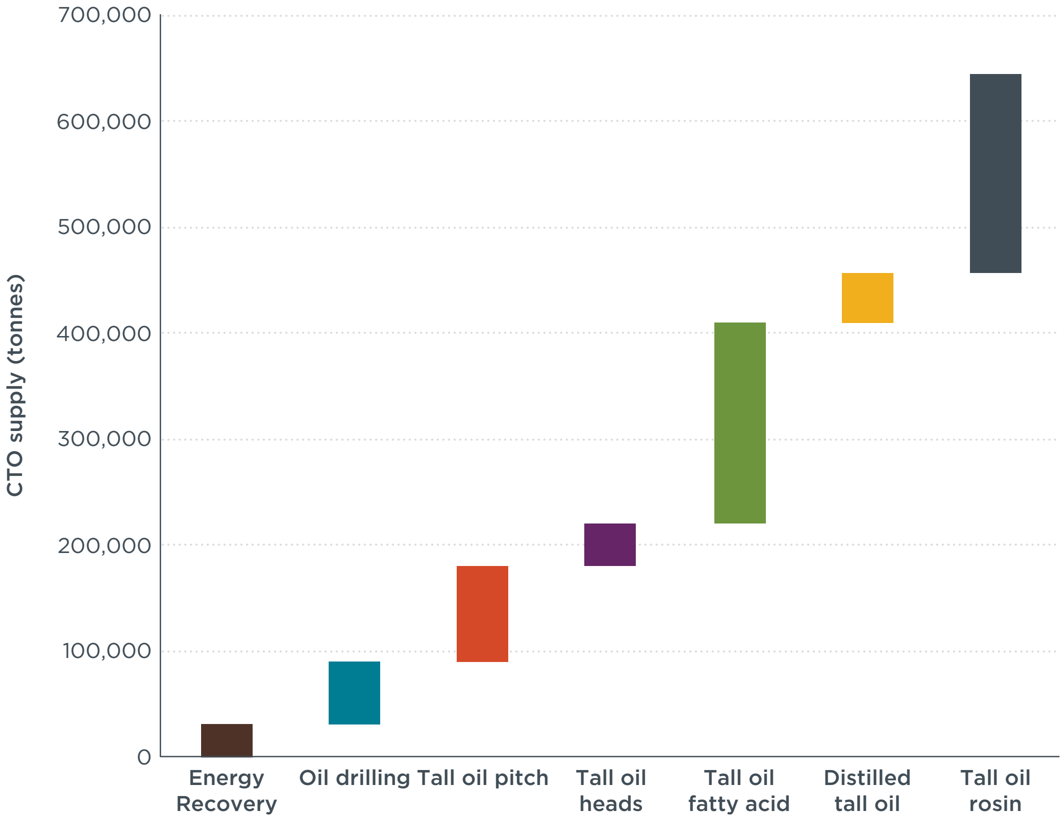

Figure 6. Illustrative order of dispatch for CTO diversion in the United States

Whereas under the average displacement approach, the quantity of biofuel produced does not affect the estimated displacement emissions, when using the order of dispatch method, the quantity of biofuel assumed can affect the results. Indeed, depending on the quantity of feedstock diverted and the progression of end uses, the emissions can vary substantially, especially if the carbon intensity of substitutes varies. For example, in Figure 6, three of the first four uses of CTO are energy recovery and all four have fossil fuel substitutes; thus, lower quantities of CTO diversion under 200,000 tonnes will likely have higher displacement emissions than higher quantities where material substitutes begin to factor into the analysis. This is because diverting CTO from energy recovery necessitates the use of higher-emitting substitutes than those for material substitutes, which are not combusted. Figure 7, below, illustrates the impact of using an order of dispatch approach for CTO displacement relative to the average displacement approach. With a relatively smaller amount of CTO displaced, the displacement emissions are higher due to the substitution of HFO and natural gas; these decrease as the quantity of CTO diverted increases until they match the average displacement emissions at the full quantity of CTO produced in the United States. This underscores the importance of assuming a realistic quantity of feedstock diverted for the analysis when utilizing the order of dispatch approach. The emissions estimate can vary substantially based on the size of the assumed demand.

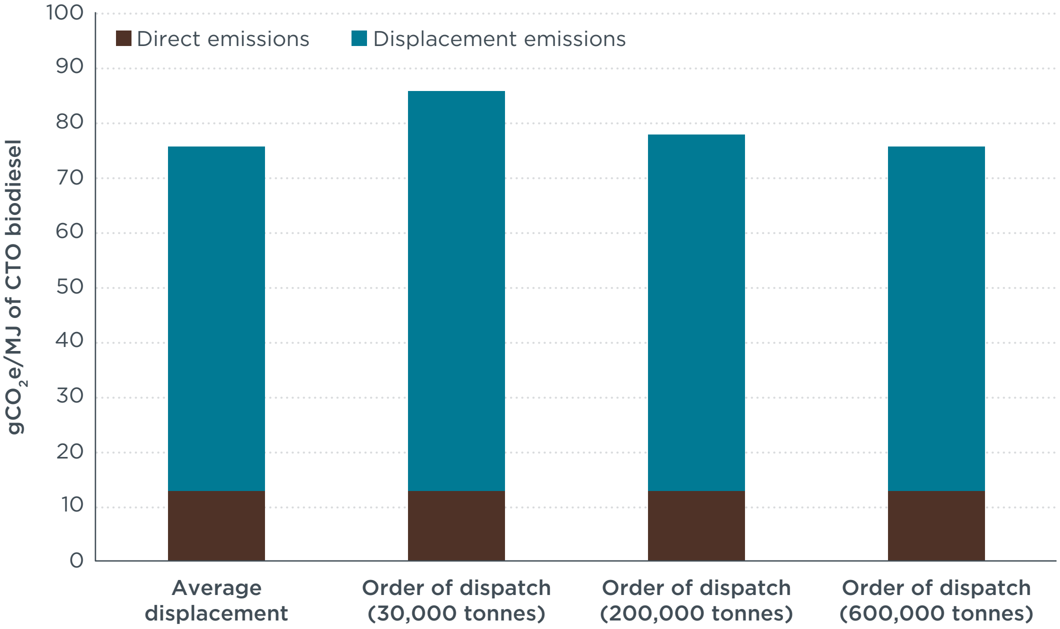

Figure 7. Comparison of displacement emissions using the average displacement approach versus illustrative order of dispatch estimates for CTO renewable diesel in the United States

Demand response

Both the average displacement approach and the order of dispatch approach oversimplify the reality of the market for biofuel feedstocks and their substitutes. In reality, prices are not fixed, and the mix of feedstocks supplied may vary according to both price and demand. Ideally, we would use price supply curves to assess the quantity of feedstock available from each existing use at a given price. Unfortunately, this level of data is likely only available for well-documented commodities such as vegetable oils, food crops, and fossil fuels. Other, more specialized products or niche uses may lack detailed supply curve data.

In a hypothetical case where multiple supply curves with varying elasticities are available for a given product's material substitutes, it would be possible to estimate the future price of a given feedstock in response to a policy change and then use those supply curves to estimate the change in usage across multiple end uses. This would identify the mix of feedstocks used to meet biofuel demand at that price. For example, if supply curves for CTO distillation products were available and suggested that usage for energy recovery was more elastic than the CTO usage in distillation for specialized uses such as for adhesives, then we could expect that a greater quantity of CTO displacement would come from energy recovery. In response to a CTO price increase, we would be able to input the change in price across end uses and estimate the relative contribution from diverting each end use to determine the overall mix diverted to meet the new demand. However, the data necessary to use this approach is not likely to be available in practice.

Accounting for existing uses in energy

In cases where the existing use for a given material is combustion for energy, diverting it to produce energy for a different sector may necessitate substitution by fossil fuels for the original use. This is a potentially significant source of indirect emissions. Deciding whether and how to incorporate existing bioenergy uses may therefore have a substantial impact on estimates of displacement emissions. ICF International (2015) recommended excluding existing uses for biofuel and bioenergy, and suggested that including these uses in effect prioritizes those uses over transport fuels and contributes to a circular effect in identifying the feedstock that is displaced. ICF argued that a displacement analysis should not make a determination about the ideal energy application for a given feedstock. Likewise, Brander et al. (2009) cited circular effects as a key methodological challenge for displacement analysis, and argued that assessing the impact of existing uses for energy for a given material could necessitate another set of displacement analyses for substitute materials, adding unnecessary complexity to the assessment.

However, if we ignore the existing energy utilization for a given feedstock, there is a large risk that the displacement analysis will fail to take into account the real-world impact of feedstock diversion. In the case of fuels policies in particular, ignoring existing energy usage for displacement analysis presumes that avoiding petroleum consumption is more important than avoiding other fossil fuels. This decision may create a scenario in which a feedstock is diverted from stationary combustion where it is a coal substitute in order to manufacture fuel for the transport sector, where it would displace petroleum. This outcome, presumably as a result of a policy promoting the use of biofuel, could perversely result in higher GHG emissions from combusting coal than occurred from the petroleum in the first place. This outcome may be possible if biomass were diverted from use in stationary boilers in countries with high reliance on coal for power generation, such as China or India.

We assess the impact of three separate methods of accounting for existing energy usage in estimated displacement emissions, illustrated by the three columns in Figure 8, below. In the left-hand column, we assume zero displacement emissions of CTO for energy use, including the onsite combustion of CTO for energy recovery and the combustion of tall oil pitch and tall oil heads in recovery boilers. We then assume that the displacement of the remaining end products from CTO distillation bears emissions for their substitute materials, as calculated by Cashman et al. (2015) and using a weighted average displacement approach. This approach likely understates the impact of feedstock diversion and in effect prioritizes the use of CTO in transport fuels, as it ignores the likely additional use of natural gas and HFO to substitute for bioenergy uses. Using this approach yields displacement emissions of approximately 31 gCO_2e per MJ of CTO biodiesel and makes the net GHG reduction relative to conventional diesel just over 50%.

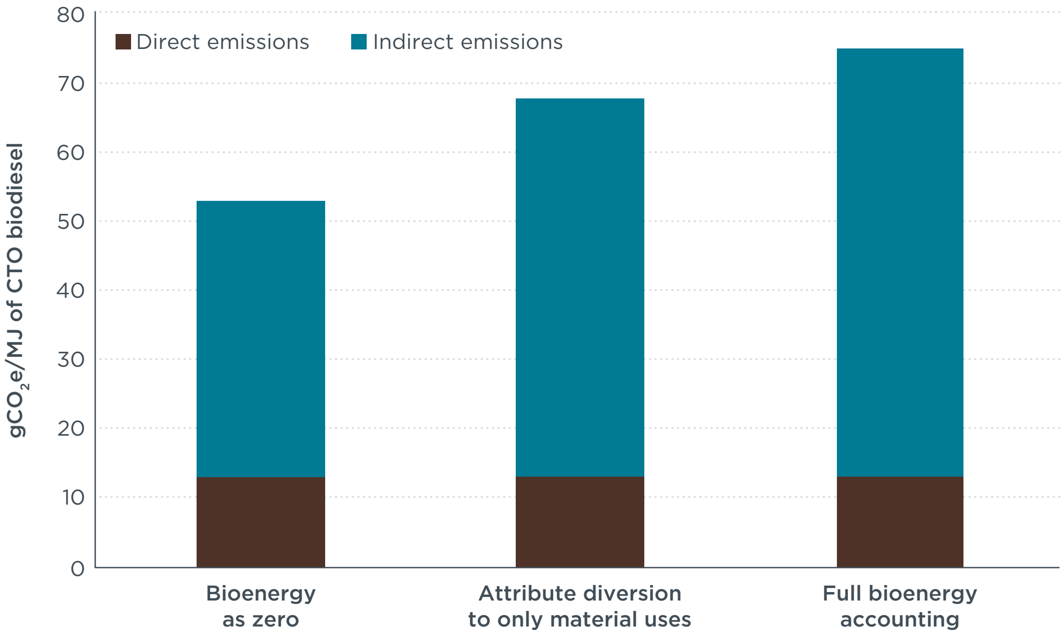

Figure 8. Comparison of displacement emissions for CTO using three different methodological approaches

To avoid the issue of circular effects, it is also possible to assume that CTO will be diverted from non-energy uses only. This approach is reflected in the middle column in Figure 8. To do this, we instead re-weight the existing material uses to exclude bioenergy uses from the weighted average of displacement impacts. In effect, we therefore assume that a disproportionate share of CTO is diverted from uses such as adhesives, coatings, and paper additives; this requires a mix of virgin vegetable oil, hydrocarbon resins, and gum resin as substitutes. This approach results in slightly higher emissions than treating existing bioenergy uses as zero, as the share of CTO used for energy in the U.S. context is relatively low, and the GHG savings from CTO biodiesel decrease to 45%. For materials with a higher share of existing uses in bioenergy, this approach would likely affect the estimated emissions to a greater extent.

In the example in the right-hand column of Figure 8, we include the displacement emissions from existing bioenergy uses for CTO into the weighted average. Both HFO and natural gas have a higher emissions intensity compared to material substitutes, and after accounting for energy density, they are approximately two to three times the carbon intensity of material substitutes.[5] Consequently, utilizing this approach will increase the displacement emissions attributable to CTO-derived biodiesel relative to the previous two methods. By factoring in the additional use of fossil fuels, we estimate an increase in displacement emissions to 54 gCO$_2$e per MJ of CTO biodiesel. This approach yields lower net GHG savings from diesel displacement of only 35%.

A fourth option, proposed by Brander et al. (2009), is a "net calculation approach" (called "net displacement" here in this paper) intended to facilitate a comparison between alternative modes of bioenergy. Using this approach, displacement effects for the sector where bioenergy has the lowest-emitting substitutes are assumed to be zero. Additionally, the impact of displacement from one bioenergy use to another is estimated to be the difference between the emissions for the lowest-emitting fossil substitute

---

[5] Emission factors and energy content for distilled CTO substitutes are presented in the Appendix.

and the emissions for the substitute in the sector being analyzed. The net calculation approach accounts for displacement from energy uses by penalizing those uses which are less efficient than the existing ones; furthermore, it allows for a consistent treatment of energy uses across sectors without introducing circular effects. Figure 9, below, compares the net displacement effect for CTO diverted from onsite combustion at a pulping mill where natural gas is the substitute with CTO diversion from the transport sector to heat and power.

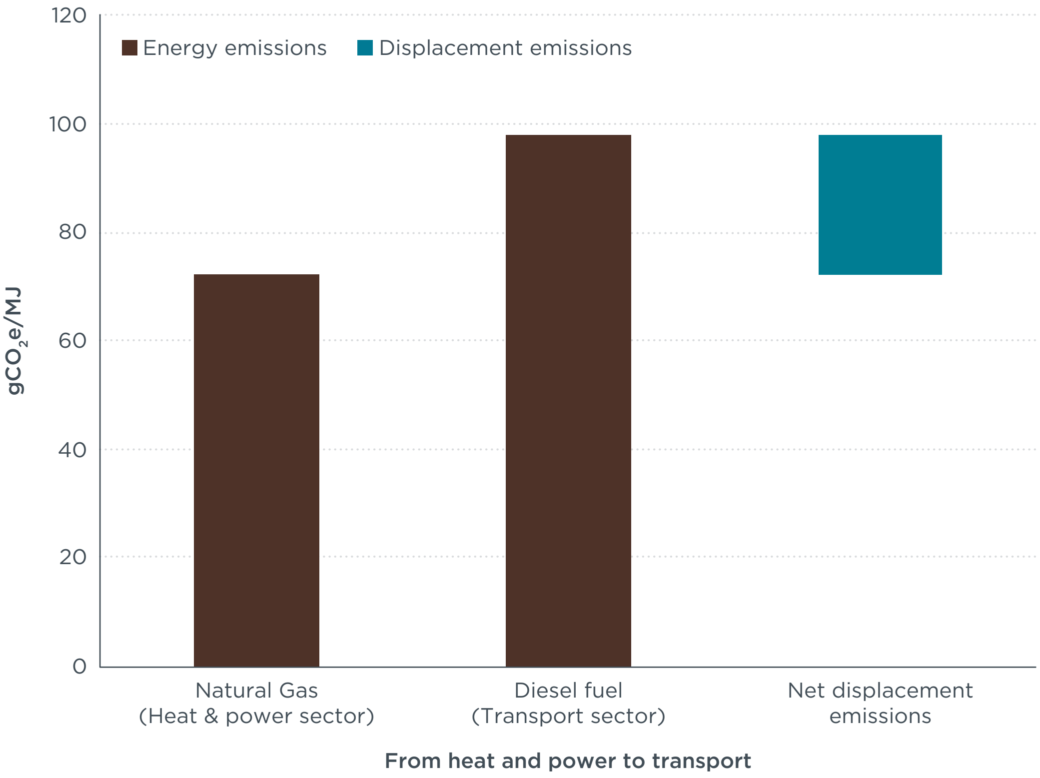

Figure 9. Displacement emissions estimated via net displacement approach for CTO used in stationary versus transport bioenergy

Using the net displacement approach, we assume that pulping mills would substitute natural gas with a life-cycle carbon intensity of approximately 72 gCO_2e per MJ for displaced CTO or CSS (GREET, 2018); this is the lowest-carbon substitute for CTO bioenergy. In the transport sector, CTO-derived biodiesel would displace conventional diesel fuel with a carbon intensity of 98 gCO_2e per tonne. Diverting CTO from heat and power would not have any displacement emissions in this analytical framework, whereas diverting CTO from transport to provide heat and power would have net displacement emissions of approximately 26 gCO_2e per MJ, assuming a 1:1 substitution on the basis of energy content.

Price-induced effects on supply and demand

In the previous sections, we assessed the impact of methodological assumptions for displacement with an assumption that biofuel feedstocks and their substitutes have a 1:1 substitution ratio based on their physical properties. In that simplified framework, a diverted feedstock is expected to be replaced with the necessary quantity of substitutes to make up for the displaced energetic or nutritional value. In reality, however, the relationship between price, supply, and consumption of various materials can be much more complex. The diversion of feedstocks can have second-order effects on the demand and supply of substitute materials, and may therefore change their relative contribution to estimates of displacement emissions.

Demand reduction

As the price of a given material increases, demand for it goes down proportionally, with the slope of that relationship forming a demand curve. Shifting biofuel feedstocks away from their existing uses increases the overall demand for their substitutes, thus increasing those substitutes' prices relative to the counterfactual case. As the prices of these substitute materials increase, we can expect the quantity utilized to decrease in turn. This demand reduction means that in practice, the substitution ratio between a diverted material and its replacements is less than 1:1.

Demand reduction in response to price increases for food commodities is typically included in ILUC models as these models estimate the shifts in agricultural activities and land use in response to demand shocks. It is clear from assessing the body of ILUC studies that demand reduction assumptions play a large role in the estimation of indirect emissions attributable to increased biofuel demand. Generally, the greater the demand reduction, the lower the displacement and ILUC emissions estimates will be. The quantity of demand reduction has a large impact on the final emissions estimates for each modeling study, as this quantity directly reduces the remaining demand that must be met through land expansion or intensification. In modeling studies using the Food and Agriculture Policy Research Institute (FAPRI) model and Global Trade Analysis Project (GTAP) ILUC models for RFS and LCFS implementation, the share of biofuel feedstock supplied through reduced consumption ranges from 0% to nearly 40% of the demand shock (Malins, Searle, & Baral, 2014). In another ILUC study commissioned by the European Commission using the GLOBIOM model, this share ranges from 0% to 42% (Valin et al., 2015). Figure 10 summarizes the quantity of feedstock supplied for biofuel production from reduced consumption in Valin et al. (2015), relative to the aforementioned GTAP and FAPRI studies.

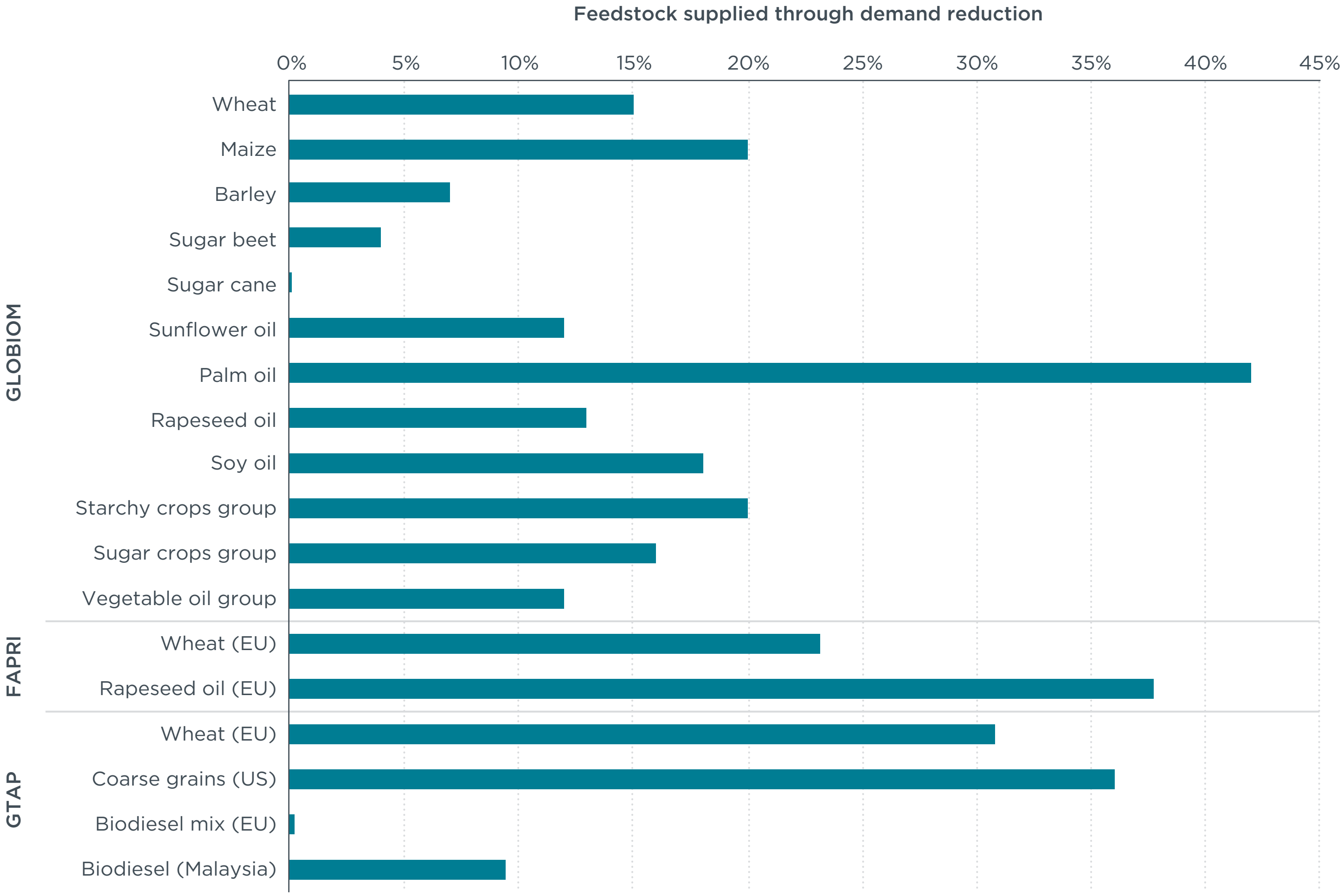

Figure 10. Comparison of demand reduction estimates across various ILUC models. Source: Valin et al. (2015); Malins et al. (2014)

Outside of using economic models with supply and demand curves for various commodities, it may be prohibitively difficult to estimate the quantity of demand reduction for a given material in a displacement analysis. Instead, it is in most cases necessary to use a flat assumption when accounting for this effect. Brander et al. (2009) called for considering demand reduction in its proposed methodology but did not provide firm guidance on selecting a value. The authors assumed demand reduction of 25% for one of their case studies for wheat straw ethanol to account for farmers using less straw in animal bedding overall in response to higher prices. Searle et al. (2017) and Malins (2017) both utilized a uniform, 10% demand reduction assumption for material substitutes as a conservative assumption that falls within the range of expected values for food commodities estimated via ILUC modeling. To illustrate this effect, we apply demand reduction to the case of grain substitution for UCO biodiesel in Figure 11, using various levels of demand reduction assumptions in order to assess how it impacts the original estimate of displacement emissions. The figure illustrates a linear relationship between the demand reduction assumption and estimated displacement emissions—the displacement emissions estimate shrinks proportionally as the assumed demand reduction increases. The decision to include demand reduction in a displacement analysis improves the quality of the results by more closely aligning with real-world behavior. However, the choice of any particular value in the absence of strong evidence adds uncertainty to the final result.

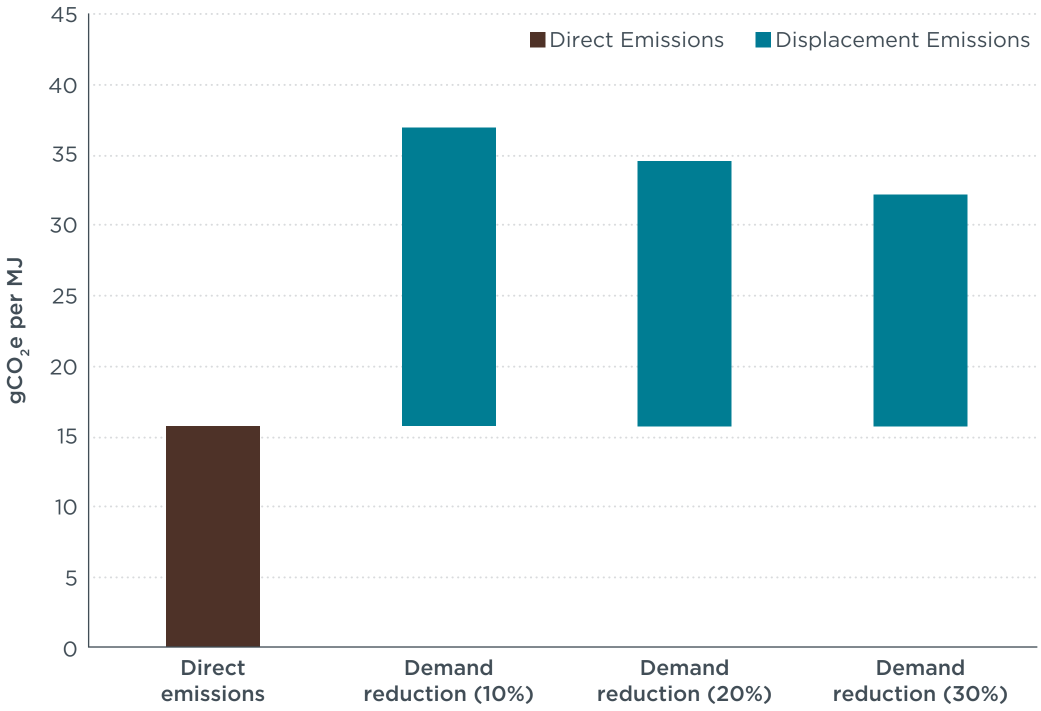

Figure 11. Impact of demand reduction assumptions on displacement emissions for UCO biodiesel

Renewable rebound effects

Diverting materials from heat and power generation to biofuel production does not necessarily lead to increased fossil fuel use in heat and power. Policies such as the EU's RED mandate a certain share of renewables in the heat and power sector, and diverting bioenergy from those sectors to supply transport fuels may prompt the use of additional renewables to drive those mandates. Malins (2017) and Searle et al. (2017) both accounted for this effect in their displacement analyses. This effect, called the "renewable rebound" in Malins (2017), is calculated based on the assumption that a loss of renewable energy for heat and power in one location causes a shortfall that must be recouped in other locations in that country. In countries without renewable energy mandates, there would be no incentive to replace diverted bioenergy with renewable energy instead of fossil fuels. The renewable rebound should be factored into a displacement analysis in any region with a renewable energy mandate, such as the EU's RED and state-level renewable portfolio standards in the United States, if that mandate is binding.

Quantifying the renewable rebound effect necessitates a series of assumptions about the degree to which bioenergy fills the gap in the context of a binding mandate and the carbon intensities of the new renewable energy sources. Malins (2017) assumed that for biofuel feedstocks used for compliance with the RED II targets, 90% of the replacement electricity supply would be met with renewables and the remaining 10% would be met with fossil fuels. From there, the author assumed that the shortfall in bioenergy caused by material diversion in the European Union would be met with a 50/50 mix of biomass energy and zero-carbon electricity from solar power and wind, with carbon intensities of 44.5 gCO_2e/MJ and 0 gCO_2e/MJ, respectively. Relative to the projected average marginal source of electricity in the European Union in 2030 of 111 gCO_2e/MJ, the average carbon savings from this mix would be approximately 80%.

To explore the effect of the renewable rebound on displacement emissions, we examine the EU case of diverting tall oil pitch away from direct combustion in a recovery boiler presented by Malins (2017). The emissions sources and reductions that the author used to assemble the net displacement emissions are detailed in Figure 12. The diagram illustrates different components of the life-cycle emissions factor for tall oil pitch-derived biofuel sequentially, from left to right and normalized in units of gCO_2e per MJ of biofuel. In this case, the author assumed that the tall oil pitch would be directly replaced by a 50/50 mix of HFO and natural gas on an energy equivalent basis, and this results in high displacement emissions for fossil fuel substitution by HFO (+103 gCO_2e/MJ), illustrated in black. This is then decreased by 10% to account for demand reduction (-10.3 gCO_2/MJ), illustrated in orange. From there, we assume that the new renewable energy generation results in a credit of -86.7 gCO_2e/MJ, illustrated in green, after accounting for boiler efficiency. Lastly, we reduce the renewable rebound by 10% to account for the author's assumption that the mandate is only 90% binding (+8.7gCO_2e/MJ); this reflects that a portion of the diverted energy is offset by increased fossil fuel use. Overall, this yields a net displacement estimate of 15 gCO_2e/MJ for tall oil pitch, in the final blue bar.

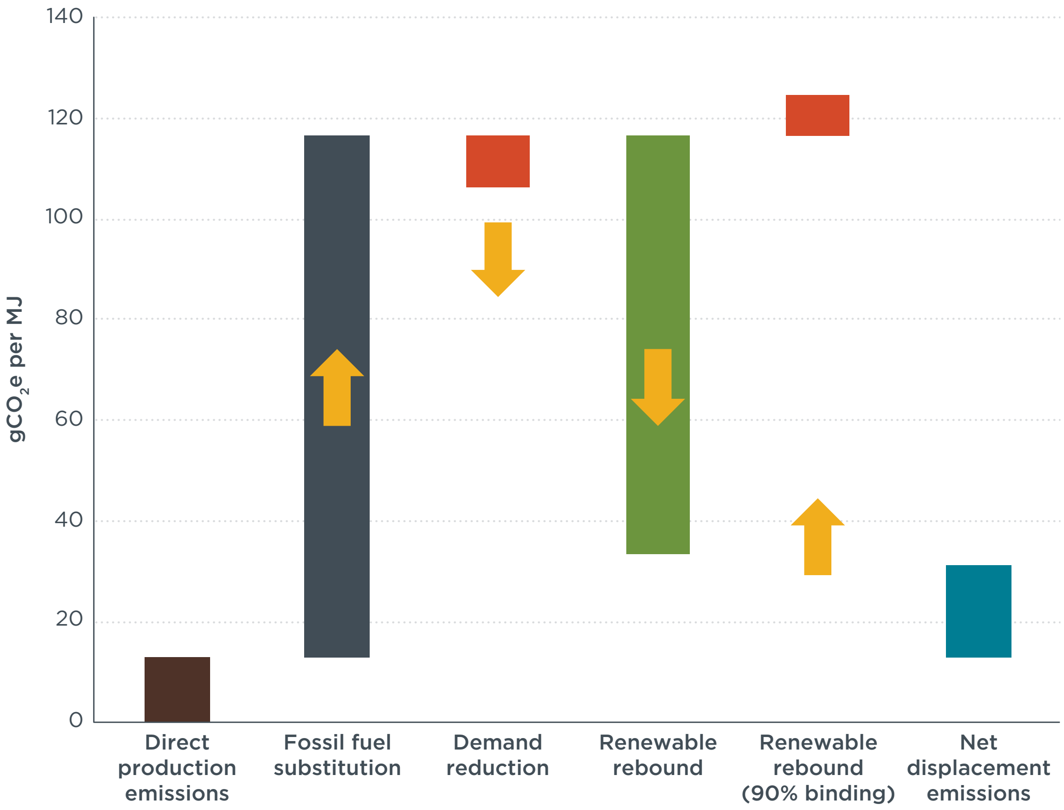

Figure 12. Estimated displacement emissions for tall oil pitch when factoring in renewable rebound effect in the European Union. *Note: Adapted from Malins (2017).*

It is clear from the example of tall oil pitch that the renewable rebound is a critical assumption for those materials with substantial existing uses for bioenergy, as emissions from new renewable energy deployment largely offset the additional HFO consumption. However, this effect is highly sensitive to the renewable energy policy context. In regions without a renewable energy mandate, or one that is exceeded or not enforced, there would be no renewable rebound effect and therefore the net displacement emissions for tall oil pitch would be substantially higher in this example. Furthermore, the magnitude of the renewable rebound effect rests on assumptions about the future marginal renewable electricity carbon intensity, which can vary by region and over time. In some areas, a greater share could come from zero-carbon wind energy; other regions may use a greater share of higher-carbon biomass combustion.

A related decision is whether to account for any rebound effects for fossil fuels displaced by new biofuel deployment. As the demand for fossil fuels decreases through the deployment of alternative fuels, the price of petroleum is expected to drop. Some have argued that this effect, called the fossil fuel rebound effect or indirect fuel use change, can partially offset the carbon savings from biofuels policies (Rajagopal, 2016; Hill, Tajibaeva, & Polasky, 2016). The fossil fuel rebound effect can be quantified as a value from 0% to 100%, and it represents the increase in fossil fuel consumption due to the price reduction relative to the amount of fossil fuel displaced by biofuel. For example, a fossil fuel rebound of 50% would mean that a 10% biofuel blending mandate for gasoline would only have the effect of displacing 5% of gasoline consumption on net.

In a review of indirect sources of emissions from fossil fuels, Malins et al. (2014) found that the range in estimated rebound effects varies from 0%–90%, with most estimates falling in between 20%–50%. Life-cycle modeling for most biofuels does not include this effect. On the higher end of the range, this would undo all the carbon savings from several biofuel pathways. For example, if an indirect fuel-use change factor of 30% was applied to the tall oil pitch-derived biofuel assessed by Malins (2017), there would be additional indirect emissions from the market response of lower HFO prices; the fossil fuel substitution emissions would consequently increase by 30% and this would increase net displacement emissions to 45 gCO_2e/MJ. However, Malins et al. (2014) concluded that this effect is highly uncertain and estimates vary widely across studies with little consensus in the literature. Thus, it would be difficult to incorporate a fossil fuel rebound in a displacement analysis.

Supply-side price responses

For some by-products, it may be possible to increase supply given sufficient demand. For these materials, it may be possible to expand the scope of the displacement analysis to include this market-mediated effect. For example, in the case of CTO biodiesel in the United States, there is substantial flexibility for additional acidulation of CSS to produce greater quantities (Peters & Stojcheva, 2017). Peters and Stojcheva (2017) described the market for CTO as somewhat varied depending on the quality of the CTO; higher quality CTO fetches a premium from distillers and low-quality CTO is more suitable for biofuel production. In this case, it may be more cost-effective to increase acidulation at pulp mills to produce greater quantities of CTO rather than divert higher-grade CTO from distillers.

Although the pulping industry has some ability to expand CTO production and mitigate diversion from higher-value existing uses, this would require new inputs for onsite energy. Greater quantities of CSS can be acidulated rather than combusted, and Malins (2017) assumed that prior to diversion, a share of the additional CTO demand in the European Union from biofuels would come from increased acidulation. Likewise, Peters and Stojcheva (2017) estimated that there is substantial capacity for increased acidulation in the U.S. pulping industry—roughly 90,000 tonnes using existing acidulators, and another 520,000 tonnes through the installation of new acidulators. Market-mediated supply expansions like these would be difficult to estimate within the context of a displacement assessment, due to the need to price not only the cost of the foregone energy but in some cases the added acidulation infrastructure.

Though the production of wastes is generally not responsive to demand, there are other opportunities to increase supply. Greenea (2016) estimated that in the European Union, there is some flexibility in the UCO marketplace, with opportunities to slightly increase UCO supply through increased collection from centralized sources. In the longer-term with sufficient prices and policies, it would even be possible to increase collection of household UCO, though the utilization of household UCO supply comes with substantial economic and logistical barriers. According to Baldino et al. (2020), there is some evidence that UCO collection in the United States has increased and exports have decreased over the past decade; this was concurrent with additional demand from the biofuel industry.

Supply-side responses may also be considered for by-products with high per-kilogram value that nevertheless comprise a small share of their overall product system. Tallow, for example, makes up less than 3% of the value of cattle and therefore its supply is generally considered to be inelastic to price (ICF, 2015). Changes to the value of tallow—even substantial ones—would only have a minor effect on the price of the whole cattle, but may still result in some marginal increase in cattle production. The increased cattle production attributable to that price increase would then result in a greater quantity of tallow for biofuel production while reducing the impacts on existing markets for tallow.

To illustrate, we take a theoretical example of how increased demand for tallow in biofuel might increase tallow supply. Baldino et al. (2020) estimated that approximately 11% of inedible tallow, or approximately 181,000 tonnes, goes toward biofuels in the United States. We might assume that an additional 50% of U.S. tallow production, about 800,000 tonnes, will be in demand for biofuels and that the tallow price responds proportionally, increasing by 50%. This would increase the value of the overall cattle by 1.4%. If we then assume an own-price supply elasticity for slaughter cattle of 0.82 based on Marsh (2007), that 1.4% price increase would translate into 1.14% more cattle production. The most recent U.S. GHG inventory estimates that the U.S. beef industry emits approximately 138 million tonnes CO_2e from enteric fermentation and manure management; this does not include upstream emissions from farm management and feed production. A 1.14% increase then translates into 1.57 million tonnes CO_2e, but only 22,000 additional tonnes of tallow, assuming a proportional 1.14% increase from total U.S. tallow production. We attribute the added cattle industry emissions to the new 800,000 tonnes of tallow demand, and estimate a displacement effect of 53 gCO_2/eMJ.[6]

As the new supply only met a small portion, 2.8%, of the additional demand for tallow, the remainder will come from diversion from existing uses and therefore would be assessed using a conventional displacement analysis. Based on the work of Baldino et al. (2020) on the existing uses of inedible tallow, we therefore assume that 20% of the remaining demand will come from livestock feed and 80% from oleochemicals, where Baldino et al. (2020) identified the primary replacements as corn grain and palm oil, respectively. Using the average displacement approach, we estimate displacement emissions of 76 gCO2e/MJ for diverted tallow. If we include the increase in supply, the total weighted average decreases to 75.3 gCO2e/MJ.

This approach is prohibitively complex and requires abundant, high-quality data for the elasticities of the materials and production systems in question. The demand shock assumptions possible for one feedstock may not translate to others with very different market dynamics, and this creates inconsistency between various feedstocks.

---

[6] Assuming a conversion yield of 7.5 lbs of tallow per gallon of biodiesel

Furthermore, accounting for supply increase may not substantially change the result in some cases; the final result here for tallow is almost identical to that estimated using the simpler, average displacement approach because the shift in total supply is so small. For tallow, we have to make some assumptions due to the lack of quality data. This could be even more difficult for other feedstocks with smaller or more specialized markets, such as CTO. Calculating the emissions for the expansion of large, varied industries and then attributing those emissions to individual by-products or co-products introduces another element of complexity and uncertainty. The decision of whether to attempt accounting for supply-side price responses should be informed by both the complexity (and thus uncertainty) of the production system and market and the expected importance of the effect in any particular case.

Recommendations

Having presented a variety of methodological considerations for developing a displacement analysis and illustrating their impact on the final results, it is clear that there is no one correct way to evaluate displacement emissions and that the effects of these methodological choices warrant consideration in biofuels policy. Based on the discussion above, we identify several suggestions for those analyzing these emissions in the future:

- **Tailor the assessment to answer specific questions.** In order to reduce uncertainty and produce usable results, policymakers should strive for a narrow scope when developing a displacement analysis. Precisely defining a given feedstock, its region, and the quantity demanded facilitates a more accurate definition of existing uses and alternative materials and production systems.
- **Until non-transport sectors account for displacement effects, it is appropriate to account for bioenergy displacement.** Ignoring the displacement of bioenergy in other sectors when assessing transport fuels innately prioritizes the reduction of emissions in transport relative to other sectors and overestimates the quantity of GHG emission reductions achievable by some pathways. Incorporating these emissions sources into the analysis is important to highlight the risks for feedstocks that have large existing uses for energy and where fossil fuels are likely to be used as substitutes.
- **Market-mediated effects can add substantial complexity to the analysis, but are still worth including.** Market responses to biofuel policies are rarely simple to model and often require substantial quantities of data to understand and flesh out. However, ignoring these effects in a displacement analysis would gloss over important behavior. Demand reduction and supply response are important reactions to consider in response to a demand shock for a given feedstock, and to the extent it is possible to incorporate these into a scenario, the scenario will more closely reflect reality.
- **Where possible, assess different materials consistently.** Many of the examples of analytical choices presented above use *ad hoc* calculations to assess displacement emissions for a given feedstock. For some feedstocks, data limitations mean it is easier to assess using an average displacement approach, and for others, it is possible to use a more data-intensive approach to assess order of dispatch or the expansion of supply. Within the context of a policy promoting multiple feedstocks, however, it is important to strive for consistency when evaluating the displacement effects of multiple feedstocks. This will help to ensure that the policy is not treating them differently.

References

Aryan, V., and Kraft, A. (2020). *The crude tall oil value chain: Global availability and the influence of regional energy policies.* Fraunhofer Institute for Environmental, Safety, and Energy Technology.

Baldino, C., Searle, S., & Zhou, Y. (2020). *Alternative uses and substitutes for wastes, residues, and by-products utilized in alternative fuel production.* Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/alternative-wastes-residues-by-products-us-2020

Brander, M., Hutchison, C., Sherrington, C., Ballinger, A., Beswick, C., Baddeley, A., . . . Murphy, R. (2009). *Methodology and evidence base on the indirect greenhouse gas effects of using wastes, residues, and by-products for biofuels and bioenergy.* Ecometrica: Report to the U.K. Renewable Fuels Agency and the Department for Energy and Climate Change. Retrieved from https://www.lowcvp.org.uk/resource-library/reports-and-studies.htm

Brander, M., & Wylie, C. (2011). The use of substitution in attributional life cycle assessment. *Greenhouse Gas Measurement and Management*, *1*(3-4), 161–166. doi: 10.1080/20430779.2011.637670

California Air Resources Board. (2019). LCFS pathway certified carbon intensities. Retrieved from https://ww3.arb.ca.gov/fuels/lcfs/fuelpathways/pathwaytable.htm.

California Air Resources Board. (2020). Low-Carbon Fuel Standard—About. Retrieved from https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard/about.

Carnegie Endowment (2020). Oil-Climate Index, U.S. Texas Eagle Ford Black Oil Zone. Retrieved from http://oci.carnegieendowment.org/#oil/u.s.-texas-eagle-ford-black-oil-zone

Cashman, S., Moran, K., & Gaglione, A. (2015). Greenhouse gas and energy life cycle assessment of pine chemicals derived from crude tall oil and their substitutes. *Journal of Industrial Ecology, 20*(5), 1108-1121. doi:10.1111/jiec.12370

De Almeida, D. G., Soares Da Silva, R., de C. F., Luna, J. M., Rufino, R. D., Santos, V. A., Banat, I. M., & Sarubbo, L. A. (2016). Biosurfactants: Promising molecules for petroleum biotechnology advances. *Frontiers in Microbiology*, *7*, 1718. doi:10.3389/fmicb.2016.01718

Edwards, R., Larive, J.F., Rickeard, D., Weindorf, W., Godwin, S., Hass, H.,... Hamje, H. (2014). *Well-to-wheels analysis of future automotive fuels and powertrains in the European Context.* Joint Research Centre. Report EUR 26237 EN. Retrieved from: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC85326/wtt_report_v4a_april2014_pubsy.pdf

Energy Information Administration (2020a). Natural gas prices. Retrieved from https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm

Energy Information Administration (2020b). Weekly heating oil and propane prices. Retrieved from https://www.eia.gov/dnav/pet/pet_pri_wfr_dcus_nus_w.htm

European Parliament (2017). *Draft Opinion of the Committee on the Environment, Public Health and Food Safety for the Committee on Industry, Research and Energy on the proposal for a directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources (recast).* June 6, 2017. (COM(2016)0767 – C8-0500/2016 – 2016/0382(COD)). https://www.europarl.europa.eu/doceo/document/ENVI-PA-604700_EN.pdf

Greenea. (2016). *Analysis of the current development of household UCO collection systems in the EU*. Retrieved from the International Council on Clean Transportation, https://www. theicct.org/sites/default/files/publications/ Greenea%20Report%20Household%20 UCO%20Collection%20in%20the%20 EU_ICCT_20160629.pdf

Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model (2018). GREET 2018. Argonne National Laboratory; https://greet.es.anl.gov/.

Harrison, P., Malins, C., Searle, S., Baral, A., Turley, D., & Hopwood, L. (2014). *Wasted: Europe's untapped resource.* Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/wasted-europes-untapped-resource

Hill, J., Tajibaeva, L., & Polasky, S. (2016). Climate consequences of low-carbon fuels: The United States Renewable Fuel Standard. *Energy Policy*, *97*, 351–353. doi: 10.1016/j.enpol.2016.07.035

ICF International. (2015). *Waste, residue and by-product definitions for the California Low Carbon Fuel Standard*. Retrieved from the International Council on Clean Transportation, https://theicct.org/sites/default/files/publications/ICF_LCFS_Biofuel_Categorization_Final_Report_011816-1.pdf

Malins, C. (2017). *Waste not, want not. Understanding the greenhouse gas implications of diverting waste and residual materials to biofuel production.* Cerulogy. Retrieved from the International Council on Clean Transportation, https://theicct.org/sites/default/files/publications/Waste-not-want-not_Cerulogy-Consultant-Report_August2017_vF.pdf

Malins, C., Searle, S., & Baral, A. (2014). *A guide for the perplexed to the indirect effects of biofuels production*. Retrieved from the International Council on Clean Transportation, https://theicct.org/sites/default/files/publications/ICCT_A-Guide-for-the-Perplexed_Sept2014.pdf

O'Connell, A., Kousoulidou, M., Lonza, L., & Weindorf, W. (2019). Considerations on GHG emissions and energy balances of promising aviation biofuel pathways. *Renewable and Sustainable Energy Reviews*, *101*, 504–515. doi: 10.1016/j.rser.2018.11.033

Pelkmans, L., Goh, C.S., Junginger, M., Parhar, R., Bianco, E., Pellini, A., & Benedetti, L. (2014). *Impact of promotion mechanisms for advanced and low-iLUC biofuels on biomass markets: Used cooking oil and animal fats for biodiesel (case study)*. IEA Bioenergy Task 40. Retrieved from http://task40.ieabioenergy.com/wp-content/uploads/2013/09/t40-low-iluc-UCO-august-2014.pdf

Peters, D., & Stojcheva, V. (2017). *Crude tall oil low-ILUC risk assessment*: *Comparing global supply and demand*. Ecofys. Retrieved from https://www.upmbiofuels.com/siteassets/documents/other-publications/ecofys-crude-tall-oil-low-iluc-risk-assessment-report.pdf

Rajagopal, D. (2016). On mitigating emissions leakage under biofuel policies. *GCB Bioenergy*, *8*(2), 471–480. doi:10.1111/gcbb.12262

Reece, G., Dehue, B., Alberici, S., van de Staaij, J., Hettinga, W., Watson, P., Chudziak, C., Bauen, A., Signal, K., & Berry, A. (2008). *RFA C&S consultation document part three*. Office of the Renewable Fuels Agency. Retrieved from https://webarchive.nationalarchives.gov.uk/20091018002108/http://www.renewablefuelsagency.org/_db/_documents/RFA_C_and_S_Consultation_Part_Three.pdf

Renewable Fuel Standard Program: Grain Sorghum Oil Pathway, Final Rule, 83 Fed. Reg. 37735 (August 2, 2018) (to be codified at 40 CFR 80).

Santeramo, F. G., & Searle, S. (2019). Linking soy oil demand from the US Renewable Fuel Standard to palm oil expansion through an analysis on vegetable oil price elasticities. *Energy Policy*, *127*, 19–23. doi: 10.1016/j.enpol.2018.11.054

Searle, S. (2019, January 10). If we use livestock feed for biofuels, what will the cows eat? [Blog Post]. Retrieved from the International Council on Clean Transportation, https://theicct.org/blog/staff/if-we-use-livestock-feed-biofuels-what-will-cows-eat

Searle, S., Pavlenko, N., El Takriti, S., & Bitnere, K. (2017). *Potential greenhouse gas savings from a 2030 greenhouse gas reduction target with indirect emissions accounting for the European Union*. Retrieved from the International Council on Clean Transportation, https://theicct.org/sites/default/files/publications/RED-II-Analysis_ICCT_Working-Paper_05052017_vF.pdf

Townsend, T. J., Sparkes, D. L., Ramsden, S. J., Glithero, N. J., & Wilson, P. (2018). Wheat straw availability for bioenergy in England. *Energy Policy*, *122*, 349–357. doi: 10.1016/j.enpol.2018.07.053

U.S. Department of Agriculture. (2019). *EU biofuels annual 2019.* Retrieved from: https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Biofuels%20Annual_The%20Hague_EU-28_7-15-2019.pdf

U.S. Environmental Protection Agency, Assessment and Standards Division, Office of Transportation and Air Quality. (2010). *Renewable fuel standard program (RFS2) regulatory impact analysis*. (EPA-420-R-10-006). Retrieved from https://nepis.epa.gov/ Exe/ZyPURL.cgi?Dockey=P1006DXP.txt

U.S. Environmental Protection Agency. (2014). *Food waste scoping analysis.* Retrieved from: https://www.epa.gov/sites/production/files/2016-01/documents/msw_task11-1_foodwastescopinganalysis_508_fnl.pdf

Valin, H., Peters, D., van den Berg, M., Frank, S., Havlik, P., Forsell, N., & Hamelinck, C. (2015). *The land use change impact of biofuels consumed in the EU: Quantification of area and greenhouse gas impacts*. Retrieved from the European Commission, https:// ec.europa.eu/energy/sites/ener/files/documents/Final%20 Report_GLOBIOM_publication.pdf.

Voegele, E. (2012, February 10). Finland-based UPM plans crude tall oil renewable diesel plant. *Biomass Magazine.* Retrieved from http://biomassmagazine.com/articles/7617/finland-based-upm-plans-crude-tall-oil-renewable-diesel-plant/?ref=brm

Appendix

Emission factors for displacement calculations

Material	Energy density (MJ/kg)	Emission factor (kg CO_2e/tonne)	Data source	Notes
Acrylic resin	N/A	2,628	Cashman et al. (2015)	
Alkenyl succinic anhydride (ASA)	N/A	2,167	Cashman et al. (2015)	
C5 hydrocarbon resins	N/A	1,902	Cashman et al. (2015)	
Gum rosina	N/A	461	Cashman et al. (2015)	
Gum rosin estera	N/A	461	Cashman et al. (2015)	
Heavy fuel oil	39.5	3,749	GREET Model (2018)	
Natural gas	47.1	3,477	GREET Model (2018)	
Petroleum crude	43.7	437	Carnegie Endowment (2020)	Only includes pre-combustion emissions; non-energy usage for oil drilling as a surfactant
Soy oil	37.0	2,173	Cashman et al. (2015)	Includes indirect land-use change emissions from EPA (2010)