



WHITE PAPER

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INDIRECT EMISSIONS FROM WASTE AND RESIDUE FEEDSTOCKS: 10 CASE STUDIES FROM THE UNITED STATES

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EXECUTIVE SUMMARY

Biofuels made from food crops are commonly associated with significant indirect greenhouse gas (GHG) emissions. By contrast, the remainders of food and forestry crops and other biogenic waste materials, known as by-products, wastes, and residues, often emit little carbon when used as feedstock for biofuels; indeed, they are often assigned zero upstream GHG emissions in traditional life-cycle assessments (LCA). Moreover, these secondary outputs, ranging from corn stalks and inedible rendering products to spoiled crops and sawdust, represent a small fraction of the economic value of supply chains, whether for agricultural, forestry or other products. And because wastes are a small part of the industry value chain, increased demand for them will not likely spur increased cultivation of the primary resource (crops, forest trees, cattle, and the like) and therefore will not increase GHG emissions associated with primary resource production. In sum, the characteristics of these marginal materials—they are low-carbon and unlikely to drive production of more primary product—make them attractive feedstocks for biofuels.

However, a closer look reveals that these non-food feedstocks may also spur further indirect emissions when diverted from other uses to produce biofuels. Those other uses require substitute inputs, which have their own greenhouse gas footprints. For example, inedible tallow diverted from soapmaking or livestock feed to make biofuel is no longer available to make soap and feed, which must then be made from other materials—whose associated GHG emissions may be greater than those of the low-carbon waste fat. In other words, the use of low-emissions secondary materials for biofuels may prompt the use of high-emissions materials elsewhere. (Figure ES1.)

Direct LCA



Indirect LCA

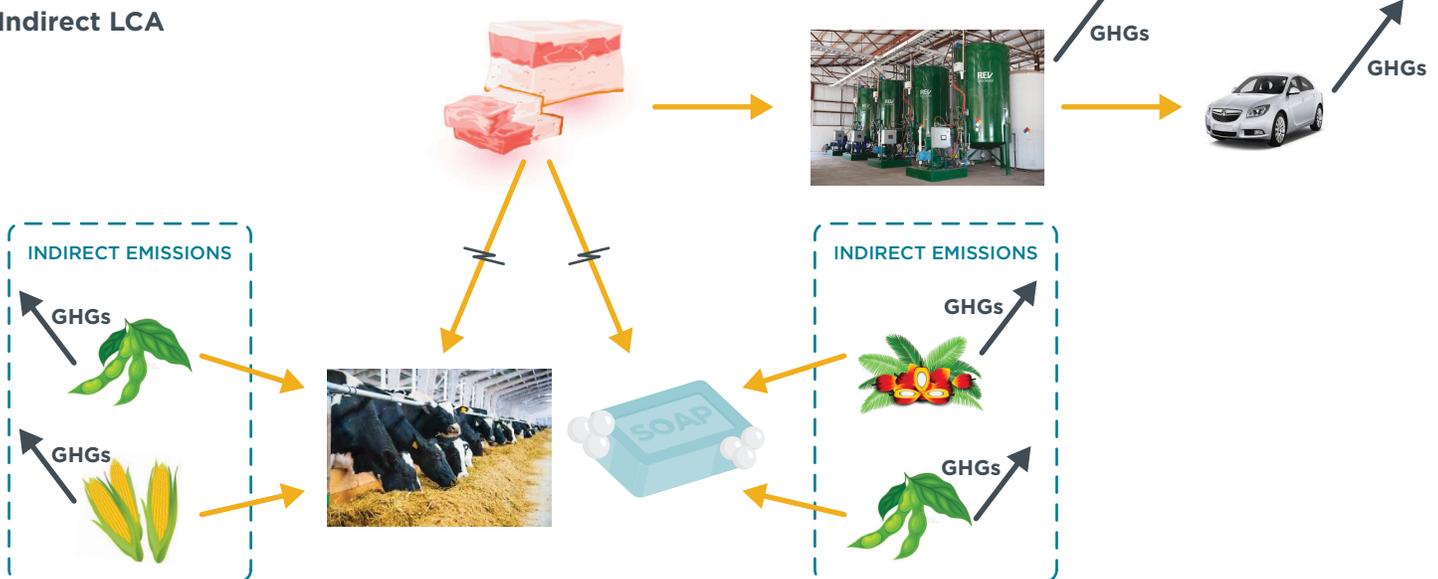


Figure ES-1. Diagram of emissions sources from direct LCA versus emissions sources from indirect LCA for tallow-derived biofuel.

The shift of material usage across sectors can result in significant GHG emission impacts. Quantifying these impacts is somewhat akin to modeling land-use change; a shift in demand for one unit of feedstock is tracked across multiple, interacting supply chains. However, for wastes, residues and by-products, current practice is to assess only the impacts of their displacement from existing uses, while not usually considering increased production of the feedstock material itself. This form of consequential LCA is known as displacement analysis. Although some displacement analyses for waste, residue, and by-product feedstocks have been conducted by researchers and environmental regulators over the past decade, the practice has not yet been widely adopted in biofuel LCA policies.

Here we develop a displacement emissions methodology and apply it to 10 waste, residue, and by-product biofuel feedstocks in the U.S. context. These materials are either current or potential biofuel feedstocks in the U.S. market and span numerous industry sectors. Figure ES-2 presents a summary of our calculations, measured in grams of carbon dioxide equivalent (g CO₂e) per Megajoule (MJ) of biofuel. Both direct emissions (in blue) from fuel production and indirect emissions from feedstock displacement (in brown) are shown in comparison with an emissions baseline for fossil fuels (the dotted line). We also incorporate a sensitivity analysis to reflect uncertainty in our final results.

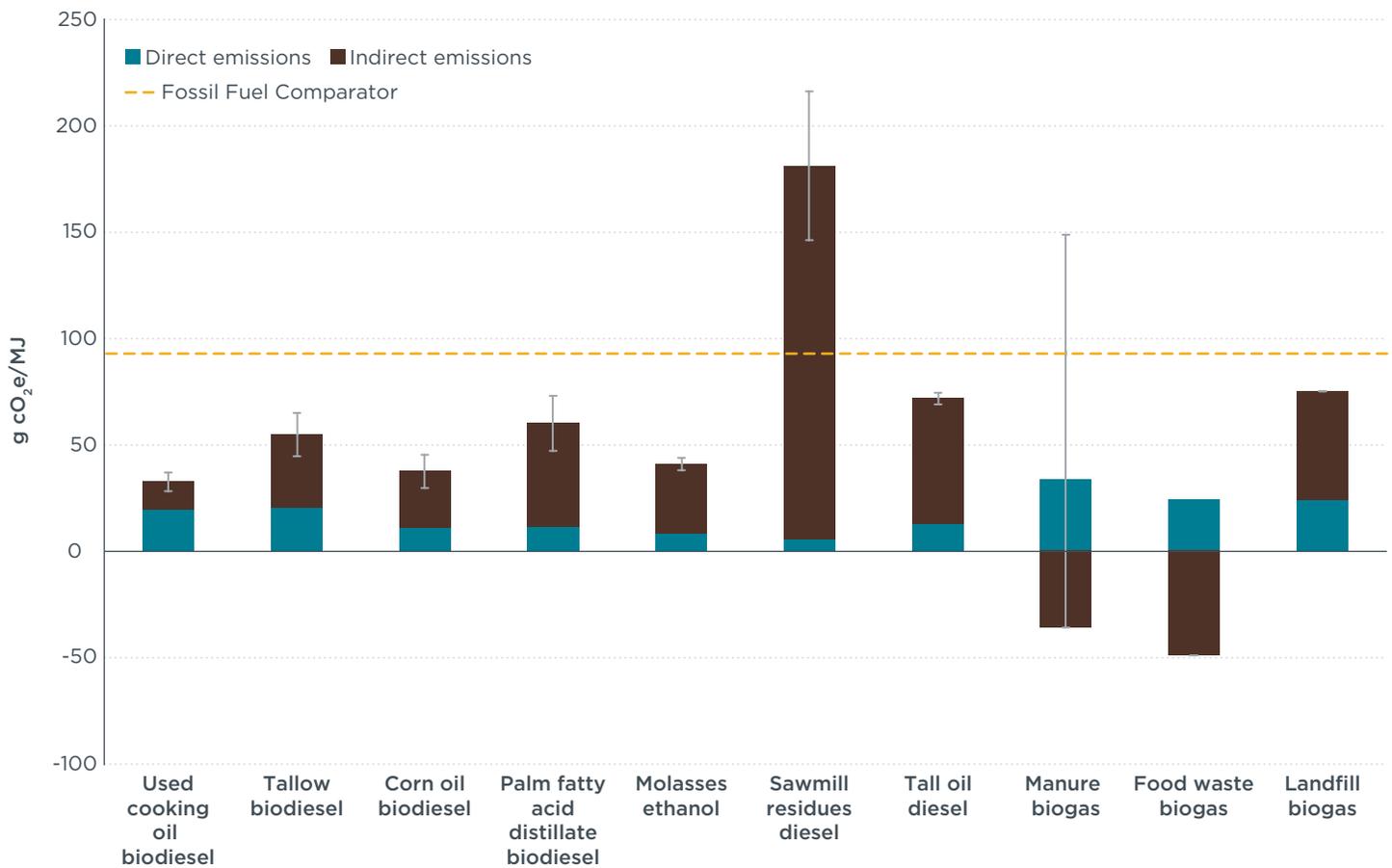


Figure ES-2. Summary of direct and indirect emissions (gCO₂e/MJ) for biofuels derived from common wastes and by-products in the U.S.

Our results highlight the effects that inclusion of displacement emissions have on the overall carbon intensity (CI) score of biofuels. While the feedstocks assessed here are generally considered wastes and residues, and therefore biofuels produced from them are typically thought to have very low GHG emissions, our analysis shows they all may have significant indirect emissions effects. Across our ten case studies, indirect emissions vary greatly, ranging between -49 gCO₂e/MJ to 176 gCO₂e/MJ. In one case, sawmill residue diesel, these impacts are so high as to render the biofuel pathway higher-GHG than that of fossil fuel. Outside the biofuels sector, sawmill residues are primarily used in heat and power production at lumbermills and as a low-cost material for the fiber products industry. Since sawmill residue's likeliest substitutes (pulpwood and natural gas) are associated with significant upstream GHG emissions, diverting this feedstock toward biofuels production results in large indirect emissions impacts.

Feedstocks can also have negative displacement effect emissions when a unit of material is diverted to biofuels. This is the case for manure and food waste biogas, the pathways with the lowest CI scores of all feedstocks analyzed. Both food waste and manure emit significant quantities of methane when they are left untreated in covered landfills, lagoons, or other disposal applications and require no material substitutes. Thus, capturing and upgrading methane gas for biofuel production results in a negative displacement effect.

Displacement analyses are one tool to help policymakers identify feedstocks with the highest risk of adverse environmental impact. Life-cycle emissions associated with biofuels consumption do not begin and end at the pump, so evaluating interacting market effects between feedstocks can inform regulators of their overall climate impact. A more thorough understanding of indirect emissions may change the prioritization of these feedstocks within a transport decarbonization strategy.

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INTRODUCTION

Displacement analysis is a method for quantifying the indirect emission impacts associated with the production of biofuels from wastes, residues and by-products. Like indirect land use change (ILUC) accounting, these analyses assess material linkages across multiple industries when a unit of biomass feedstock is consumed as a unit of transportation fuel. Biomass feedstocks are often limited in supply, so delivering a unit of fuel to the transportation market will in some cases result in its diversion from another end use. This occurs for both food-based biofuel feedstocks such as corn and soybean as well as for waste and by-product materials such as agricultural and forestry residues. A concept central to displacement analyses is that diverting feedstocks from existing uses requires the production of substitute materials to take their place, each with its own associated greenhouse gas (GHG) emissions.

The indirect effects of using wastes, residues and by-products for biofuels has long been studied. In 2008, the UK Renewable Fuels Agency (RFA) commissioned a study to investigate the indirect emission effects associated with using wastes and by-products for biofuels production (Reece et al., 2008). Interest in this topic formed out of the recognition that, although a by-product, tallow may have significant emissions impacts when used as a biofuel due to the high emissions intensity associated with its likely substitutes. Although the Reece et al. report was not incorporated into regulatory GHG accounting methodology, it was successful in its aim to “inform the future development of lifecycle methodologies for biofuels” (p.8).

Brander et al. expanded upon this work for the RFA and proposed a more detailed methodology for quantifying indirect emissions associated with biofuels consumption (2009). This methodology was applied to four case studies including molasses, tallow, straw, and municipal solid waste (MSW). Additional work on this topic has been conducted in Europe on the Renewable Energy Directive (REDII) Annex IX advanced biofuel feedstock list (Malins, 2017; Searle et al., 2017). Although displacement emissions are not explicitly taken into account in EU policy, any new additions to the EU’s advanced biofuel feedstock list must be considered in light of “the need to avoid significant distortive effects on markets for (by-)products, wastes or residues” and “the need to avoid creating an additional demand for land” (Directive EU 2018/2001). In the U.S., the Environmental Protection Agency (EPA) first applied displacement methodology in its 2018 grain sorghum oil pathway rulemaking under the federal Renewable Fuel Standard (RFS) program (Renewable Fuel Standard Program: Grain Sorghum Oil Pathway, 2018). Some policies, such as California’s Low Carbon Fuel Standard (LCFS) regulation and the EU-RED, account for avoided methane emissions for manure and landfill-derived biogas.

In this study we apply displacement methodology to 10 waste, residue, and by-product feedstocks. These feedstocks are either currently used for biofuel production in the U.S. or have the potential for expanded production. By applying displacement methodology, we can quantify the indirect emissions associated with each biofuel production pathway and gather a more complete understanding of their GHG reduction potential relative to conventional fossil fuels.

METHODOLOGY

We develop a standardized displacement methodology for calculating indirect emissions of waste, residue and by-product feedstocks in a U.S. context. Our study methodology is largely drawn from the 10-step process proposed by Brander and expanded upon in a previous ICCT report (Pavlenko & Searle, 2020). We apply this methodology to 10 different feedstocks identified in a report by Baldino et al. that assessed the supply of common U.S. biofuel feedstocks and identified likely substitutes (Baldino et al., 2020).

A key methodological step introduced in Brander et al. is identifying the order of dispatch for a feedstock used for biofuel. Most feedstocks have multiple existing end uses with varying economic value so we do not expect the entirety of supply to be diverted or “dispatched” from its existing end uses. To reflect this, order of dispatch calculations capture “the order in which existing users of the feedstock material will switch to substitute materials or alternative production systems” (Brander et al., 2009, p. 12). Under this nuanced approach, users identify economic, technical, physical, legal, and other barriers to diverting materials from existing end uses, and establish an order for displacing feedstocks up to a defined biofuel demand threshold.

One challenge in applying the order of dispatch methodology for a feedstock diverted to biofuel production is identifying the amount of biofuel produced. The greater the assumed biofuel volume, the greater the number of uses from which the feedstock will be diverted. This assumption thus has a large influence in the final estimate of displacement emissions. Unless a researcher is assessing a very specific policy proposal (for example, a mandate to use a certain volume of a single biofuel pathway), there is no certainty about how much biofuel might be produced from a feedstock at any point in time. For any particular feedstock, it is reasonable to expect that some volumes would easily be diverted from the lowest value uses, but are less likely to be diverted from other, higher value uses. This likely holds true for most materials regardless of the total amount of the material produced. Setting a single biofuel volume to analyze a range of feedstocks with varying production amounts could thus be misleading as it would result in 100% diversion from current uses for feedstocks with low production amounts. This could result in skewed displacement emission estimates: for feedstocks with low-value end uses with low substitute emissions, displacement emissions could be overestimated; for feedstocks with low-value end uses with high substitute emissions, displacement emissions could be underestimated. To reduce the impact of this problem, we assume that 50% of material supply is diverted to additional biofuel production, regardless of the production amount for any one of these feedstocks.

Although our method provides for consistency in displacement calculations, alternative methods to approximate the order-of-dispatch could be used. Ideally, the order of dispatch could be determined by establishing a cost threshold for all feedstocks above which end users are unwilling to purchase substitute materials. End uses with the lowest cost differential between feedstock and substitute would be prioritized first for dispatch, followed by end uses with the next highest cost differential. We would thus expect materials with generally expensive substitutes for existing uses to be displaced to a lesser degree than materials with generally less expensive substitutes. However, researchers are unlikely to have this much information available, so we stick to the former approach.

We outline below the steps used to calculate indirect displacement emissions for each feedstock:

Step 1. Define the material

- » Identify a waste, residue, or by-product material with inelastic supply. If available, use price information to confirm this assumption. Assume products that account for a small portion of the total economic value of a commodity (e.g. tallow) or products that are strictly waste materials (e.g. municipal solid waste) have inelastic supply.
- » Define the geographic boundaries of the analysis. Consider whether the availability assessment is limited to the U.S. and whether any constraints are set on the supply of substitute materials.

Step 2. Estimate total supply and share of uses in existing markets

- » Determine total supply of a feedstock in the given geographic boundary. Identify the quantity or portion of feedstock used in each existing application (e.g. livestock feed, oleochemicals).
- » Here, we use a consequential analysis to reflect the displacement impacts that would be expected with the production of additional biofuel volumes. Thus, in identifying total feedstock supply we do not consider the amount currently being used for biofuel. In contrast, Searle et al. (2017) conducted a historical analysis on the impacts of displacing material currently being used in biofuel from its pre-existing uses.
- » We also exclude export and import volumes and volumes currently used in the transportation sector from our supply calculations, since trade decisions are impacted by factors outside the biofuels sector.
- » Feedstock supply estimates and shares of uses in existing markets are drawn from Baldino et al. except where otherwise noted (2020).

Step 3. Define the amount of biofuel

- » For our analysis, this is set to 50% of non-biofuel feedstock supply. Alternatively, specific policy mandates can be used to establish this threshold.

Step 4a. Identify substitute materials

- » Identify substitute materials suitable to replace the diverted feedstock considering price, technical compatibility, and availability within defined geographic scope. Only select substitute materials with elastic supply to avoid secondary displacement effects. Unless otherwise noted, substitute materials are drawn from Baldino et al., (2020).

Step 4b. Determine the substitute replacement share for end uses with multiple substitute materials

- » Where multiple substitute materials might be used for one use, consider technical or economic constraints to utilizing each substitute material within each end use. When there is no discernible technical or economic advantage to using different substitute materials, assume a 1:1 split.

Step 5. Determine the order of dispatch

- » First consider any technical or physical constraints on end-use diversion (e.g., primary material has no substitutes), then assume each waste/residue feedstock will first be diverted from the end use with the lowest cost differential between the

primary feedstock and substitute material. Proceed with the remaining end uses.

- » If reliable data on substitute material costs is unavailable, prices should be roughly approximated based on a material's estimated share of market sector value, and/or prices of similar materials. An example of price estimation for the rumen-protected fats market is provided in Case Study 4 below.

Step 6. Identify life-cycle emissions for each substitute material

- » In this study, we source data from the literature and EPA's lifecycle greenhouse gas (GHG) pathways table compiled from various RFS rulemakings to determine the life-cycle emissions associated with the production of each substitute material.

Step 7. Set the substitution ratio

- » The substitution ratio reflects the quantity of substitute material used to replace a unit of diverted feedstock on a per kilogram (kg) basis. Substitution ratios can be based on physical density, metabolizable energy content, or lower heating value (LHV) of the material, depending on the most relevant characteristic of the material in that use. For fertilizer applications, the substitution ratio is based on the nutrient content of each substitute material. Examples of additional considerations for determining the substitution ratio are provided below:
 - » Compare metabolizable energy content to represent calorie replacement in the livestock feed sector
 - » Compare mass density for feedstock displacement from consumer products
 - » Compare fuel LHV energy content adjusted for average boiler efficiencies for feedstock displaced from heating applications
 - » Compare kilowatt-hour (kWh) output per volumetric flow rate (m³) values for feedstock displaced from biogas electricity generation
 - » Compare nutrient content on a dry matter basis to compare fertilizer application rates for organic and synthetic materials
- » The substitution ratio can also include a demand reduction assumption for substitute feedstock materials. This adjustment accounts for the reduction in demand for products made from the material due to increased production costs when a substitute material is used. Following Searle et al., (2017) and Malins et al. (2017), we assume a demand reduction factor of 10% in all cases.
- » Combining the above considerations, substitute feedstock emissions are based on the formula below:

$$\begin{aligned} & \text{Substitute emissions} \left(\frac{g \text{ CO}_2 e}{kg \text{ feedstock displaced}} \right) \\ &= \text{Substitute production emissions} \left(\frac{kg \text{ CO}_2 e}{kg \text{ substitute}} \right) \\ & \times \text{Substitution ratio} \left(\frac{kg \text{ substitute}}{kg \text{ feedstock displaced}} \right) \\ & \times (1 - \% \text{ demand reduction}) \times \frac{1000 g}{kg} \end{aligned}$$

Step 8. Determine the yield factor for biofuel conversion

- » Obtain fuel specification data to determine feedstock to fuel conversion yields.
 - » Here, final yield factors are reported in kg fuel per kg feedstock.

Step 9. Perform displacement emissions calculation

- » Calculate total indirect emissions for each feedstock according to the following formula:

$$\begin{aligned} & \text{Indirect displacement emissions} \left(\frac{g \text{ CO}_2 e}{\text{MJ biofuel}} \right) \\ &= \text{Substitute emissions} \left(\frac{g \text{ CO}_2 e}{\text{kg feedstock displaced}} \right) \\ & \times \text{Mass density} \left(\frac{\text{kg biofuel}}{L} \right) \times \text{Energy density}^1 \left(\frac{L}{\text{MJ biofuel}} \right) \\ & \times \text{Yield}^{-1} \left(\frac{\text{kg feedstock}}{\text{kg biofuel}} \right) \end{aligned}$$

The following sections present our displacement analysis calculations, data sources, and results for each of the 10 U.S. biofuel feedstocks.

1. CASE STUDY 1: USED COOKING OIL (UCO)

1.1 DEFINE THE MATERIAL

Used cooking oil (UCO) is comprised of discarded vegetable oils with high free fatty acid content, left over from frying and food preparation. It can be collected from household or commercial sources. Due to its low cost and ease of biofuel conversion, UCO is a common feedstock used in biodiesel (FAME), renewable diesel (HVO) and sustainable aviation fuel (SAF) production. UCO comprises one of the largest sources of credits under the California LCFS program and a significant share of the biomass-based diesel (BBD) volumes under the federal RFS (California Air Resources Board, n.d.; US EPA, 2018).

1.2 ESTIMATE TOTAL SUPPLY AND SHARE OF USES IN EXISTING MARKETS

We gather annual UCO production data from the USDA National Agricultural Statistics Service (NASS). Yellow grease is the closest proximate to UCO tracked by the NASS. The terms yellow grease and UCO are often used interchangeably; however, the former may also refer to low-grade animal fat. As of 2017, 50 thousand tonnes (kt) of UCO was used in livestock feed while a much smaller quantity, 1 kt, was used in the oleochemical industry. Within the livestock feed industry, approximately 65% of UCO is fed to poultry while the remainder is split between swine and cattle (Baldino et al., 2020). UCO has also been converted to biofuel used in the U.S. transportation sector since 2010 (Baldino et al., 2020). Currently, 26 PJ (759 kt) of UCO is consumed as biofuel which we exclude from our displacement calculations.

Additional UCO could be collected from commercial sources; however, it is difficult to calculate with any precision what total collection potential might be. Informa Economics estimated total UCO collection potential from the U.S. food service sector to be 2.1 billion tonnes, more than double current supply (2011). However, this estimate was based on numerous assumptions regarding UCO generating potential. Building out collection infrastructure to support higher volumes of UCO also remains unlikely absent concerted policy support.

1.3 DEFINE THE AMOUNT OF BIOFUEL

In the absence of complete production information, we set UCO biofuel demand equal to double its current usage in non-biofuel applications. This is equivalent to 3.5 PJ (102 kt).

1.4 IDENTIFY SUBSTITUTE MATERIALS AND DETERMINE THE REPLACEMENT SHARE FOR END USES WITH MULTIPLE SUBSTITUTES

For livestock feed, we assume that UCO diverted from beef and dairy cattle diets will be replaced by grains while UCO diverted from swine and poultry diets will be replaced by oil-based ingredients. Although cattle are fed UCO in small quantities, ruminant animals often have difficulty digesting fatty substances. This is due to the inability of microbes in the rumen to break down free fatty acids (FFAs) (Hibma, 2010). Due to this limitation, when UCO is diverted from cattle feed, we assume that grains serve as the lowest-cost calorie substitute. In the U.S., corn is the most likely replacement grain stock, making up an estimated 60% of feed composition in beef cattle diets today (Klasing, 2012).

Pigs and poultry can more readily digest fatty substances in low quantities. In the U.S., pigs are commonly fed diets with up to 5% fat content while poultry are fed diets with 1-4% fat content (Klasing, 2012). Fat ingredients are more energy dense than grains and are also available at a low cost, so we assume vegetable oils serve as the substitute for UCO diverted from swine and poultry diets. In a displacement analysis for waste and residues conducted in the EU, Malins similarly concludes that “[i]t is expected that a reduction in availability of one fatty feed material for animal ratios would result in increased use of other similar fatty materials, rather than alternative energy cereals” (Malins, 2017, p. 35).

In the UK, this practice may already be occurring. Toop et al. report that roughly 20 kt of UCO is diverted from the food manufacturing industry toward biofuel production with soy oil serving as the replacement animal feed (2013). We also select soy oil as the lowest-cost substitute with elastic supply for our analysis. Soy oil is more abundant and available at lower cost than palm oil in the U.S. (USDA Foreign Agricultural Service, 2021).

Beyond nutritional limitations, we do not expect costs to influence the share of substitute materials (i.e. grain and fats) fed to livestock. Adjusting for metabolizable energy content, we find that the cost of soybean oil is roughly two times the cost of corn. Since feed efficiency is “improved 2 percent for every 1 percent increment of added fat in growing-finishing pig diets” (University of Illinois Extension, 2002), the additional costs of soybean oil relative to its performance benefits roughly balance out.

For the oleochemicals industry, we assume that soy oil and palm oil are likely material replacements. Oleochemicals are derived from animal fats and vegetable oils and are used across a wide range of consumer products including soaps, cosmetics, surfactants, and pharmaceuticals. Palm oil is more commonly used in the U.S. oleochemicals industry than in the livestock sector, so in the absence of more detailed cost information, we assume that manufacturers will select either of these materials based on cost and availability. Differences in vegetable oil composition have a negligible effect on product performance (efeca, 2018), so we assume a 1:1 split between soy and palm substitutes.

This assumption is also justifiable from a cost standpoint. The 5-year average wholesale price of soy and palm oil in the US is \$670/MT and \$720/MT, respectively (*USDA ERS - Oil Crops Yearbook*, n.d.). Amid price fluctuations and regional trade variations, we assume that manufacturers are equally likely to substitute diverted UCO with palm or soy in the oleochemicals sector.

1.5 DETERMINE THE ORDER OF DISPATCH

The costs of establishing new collection supply chains, including writing contracts and developing collection infrastructure, present barriers for expanded UCO collection. Thus, we assume that UCO will first be diverted from its existing end uses. There are no constraints on UCO diversion from the oleochemical and livestock feed markets, nor is there a clear economic preference for maintaining current UCO consumption levels in these two sectors. In the absence of more detailed production information, we assume that the entirety of UCO used in livestock feed and oleochemicals today will be diverted toward the biofuels sector and an equivalent volume will be sourced from additional collection.

1.6 IDENTIFY LIFE-CYCLE EMISSIONS FOR EACH SUBSTITUTE MATERIAL

We obtain life-cycle emissions estimates for biomass-based feedstocks including corn, soybean oil, and palm oil from pathway assessments conducted by EPA. These assessments were published in various rulemakings under the federal Renewable Fuel Standard (RFS) program. Due to uncertainty in indirect land use change (ILUC) estimates, we incorporate a 30% uncertainty factor to emissions from the production stage of materials that substitute for corn, soybean oil, and palm oil in our sensitivity analysis. This means that material ILUC emissions are increased or lowered by 30%, reflected in the error bars in Figure ES-1. We apply this same factor to all relevant case studies.

We assume that the share of UCO biodiesel demand met through additional UCO collection has zero displacement emissions, since it is not diverted from existing uses in livestock feed or oleochemicals. This portion of UCO supply is considered a waste product with no existing end uses. If the share of UCO sourced from additional collection is higher than our central estimate (50% biofuel demand), indirect emissions would decrease. Using Informa Economic's UCO collection potential as an upper bound, we calculate that indirect emissions for UCO biodiesel could range between 2.0 and 13.2 gCO₂e/MJ (Figure 1).

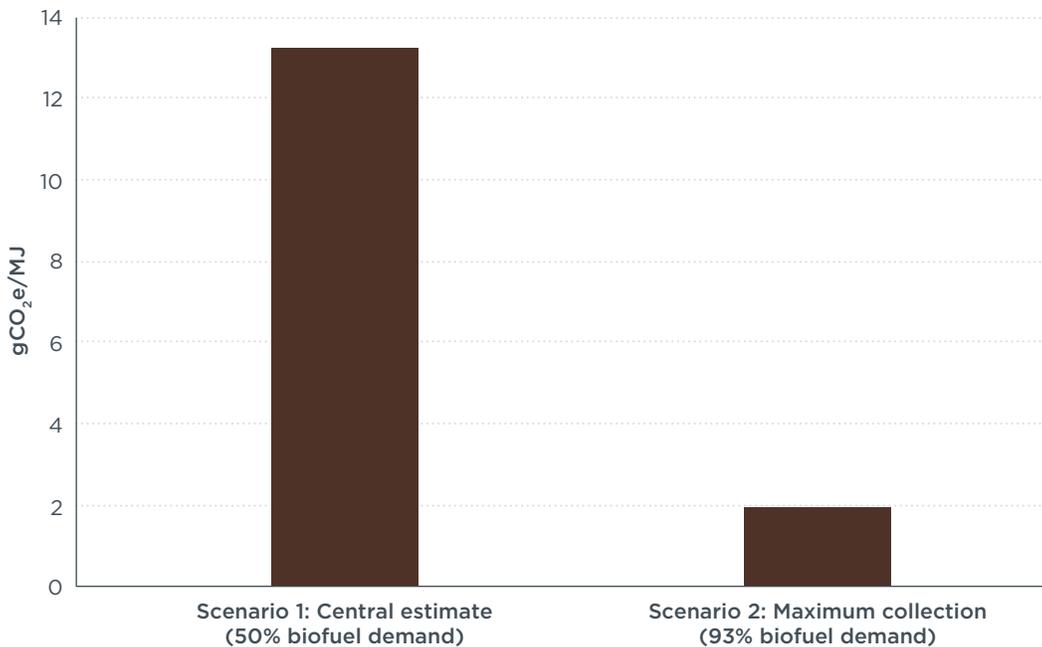


Figure 1. Indirect emissions from additional UCO collection. Label parentheses represent the share of biofuel demand displaced from additional UCO collection.

1.7 DETERMINE THE SUBSTITUTION RATIO

We compare the metabolizable energy content of corn and UCO to determine the substitution rate on a per-kg basis for cattle and dairy diets. We draw data from feed tables published by the French agricultural institutions INRAE, CIRAD and AFZ to determine metabolizable energy content by livestock type reported in MJ per kg (Institut national de la recherche agronomique (INRAE) et al., n.d.). We did not identify any feedstock composition data for raw yellow grease so we use tallow values as a

proxy. Using this data, we estimate that one kg of diverted UCO will be replaced with 2.7 kg of corn. We assume that differences in nutritional content between fats and vegetable oils are negligible from the farmer's standpoint. Thus, we assume a 1:1 soy oil to UCO substitution ratio in swine and poultry diets.

Vegetable oils and fats are largely interchangeable in the oleochemicals industry so we assume a 1:1 substitution ratio based on a mass comparison of UCO, palm oil, and soy oil.

1.8 DETERMINE THE YIELD FACTOR FOR BIOFUEL CONVERSION

For UCO, we source yield estimates for both bio- and renewable diesel (HVO) using high-FFA oils from GREET for a conversion rate of 0.91 for biodiesel and 0.85 for HVO on a kg fuel per kg feedstock basis.

1.9 PERFORM DISPLACEMENT EMISSIONS CALCULATION

Applying Formula 2, we calculate total indirect displacement emissions to be 13.2 g CO₂e/MJ for UCO-derived biodiesel and 12.2 g CO₂e/MJ for UCO-derived HVO.

2. CASE STUDY 2: INEDIBLE TALLOW

2.1 DEFINE THE MATERIAL

Inedible tallow is classified as waste material produced at independent rendering plants that are not bound by U.S. Department of Agriculture inspection standards (U.S. Environmental Protection Agency, 1995). Unlike edible tallow, it is unfit for human consumption.

Tallow has high free fatty acid content and can be readily converted to biodiesel, renewable diesel, and sustainable aviation fuel via the hydroprocessed esters and fatty acids (HEFA) process.

2.2 ESTIMATE TOTAL SUPPLY AND SHARE OF USES IN EXISTING MARKETS

Like UCO, inedible tallow is used outside the biofuels sector in livestock feed and oleochemical applications. It is also used in pet food to add fat and improve palatability (Pet Food Institute, 2008). According to the latest Census data, approximately 160 kt of tallow is used in livestock feed, 160 kt in pet food and 500 kt in the oleochemicals industry. An additional 180 kt is converted to biofuels. Although the USDA predicts that poultry and meat production, and thus tallow supply, will increase over the next decade (O'Donoghue et al., 2019), this increase will be driven by external drivers such as trade rather than U.S. biofuel demand. Moreover, our displacement analysis is conducted for present day, so future feedstock availability estimates are omitted from our analysis.

2.3 DEFINE THE AMOUNT OF BIOFUEL

We set demand for tallow-derived biofuel at 14 PJ (410 kt), or half of available supply.

2.4 IDENTIFY SUBSTITUTE MATERIALS AND DETERMINE THE REPLACEMENT SHARE FOR EACH END USE

As with UCO, corn and soy oil are likely substitutes for inedible tallow diverted from livestock feed. Soy oil is expected to replace tallow used in swine and poultry diets while corn replaces tallow used in ruminant diets including beef and dairy cattle. To determine the substitute replacement rate, we draw upon tallow consumption rates by livestock type reported by Baldino et al (2020). According to industry data, roughly 50% of inedible tallow is fed to cattle, 30% to swine and 20% to poultry. Considering that half of tallow will be replaced by corn and the remainder by soy oil, this sums to a 1:1 fats to grains substitution split.

For oleochemicals, we again assume a 1:1 palm/soy oil replacement for diverted tallow. Previous studies have found palm oil to be the marginal unit of replacement for diverted animal fats in European markets (Chudziak & Haye, 2016), due to its physical similarities and degree of saturation. However, soy oil is more abundant and available at lower cost in the U.S. In the absence of more detailed cost evaluation, we assume that soy and palm oil are equally likely to replace tallow diverted from the oleochemical industry.

2.5 DETERMINE THE ORDER OF DISPATCH

Tallow has numerous fat and oil substitutes in the livestock feed and oleochemicals sectors including corn, soy oil, and palm oil. The cost of its substitutes on a kg replacement basis are roughly the same considering the performance data outlined

in Case Study 1 above. Tallow can also be diverted from pet food and substituted with corn, although this may affect the quality and palatability of the end product (Baldino et al., 2020). Thus, we assume tallow is first diverted from livestock feed and oleochemicals up to the 410 kt biofuel demand threshold. Since there are no technical or economic advantages to diverting tallow from either end use, we assume it is dispatched at a rate equivalent to its current share of consumption (Table 1).

Table 1. Estimated tallow diversion ratio by end use

End use	Consumption (kt)	Quantity Diverted (kt)	Diversion ratio
Livestock feed	160	99	24%
Oleochemicals	500	311	76%
Total	660	410	100%

2.6 IDENTIFY LIFE-CYCLE EMISSIONS FOR EACH SUBSTITUTE MATERIAL

Once again we source data from RFS pathway assessments for the life-cycle GHG emissions for corn, soybean oil, and palm oil.

2.7 DETERMINE THE SUBSTITUTION RATIO

We calculate the substitution ratio for tallow diverted from beef and dairy cattle diets by comparing its metabolizable energy content to that of corn. We draw data from the INRAE-CIRAD-AFZ feed tables for nutritional feed data by livestock type. Since we assume the same metabolizable energy content for tallow and UCO in ruminant animals, we again calculate that one kg of diverted feedstock will be replaced with 2.7 kg of corn. Differences in nutritional content between primary and substitute fats and vegetable oil substitutes are negligible, so we assume a 1:1 soy oil-to-tallow substitution ratio in swine and poultry diets.

As above, we assume a 1:1 substitution ratio for the oleochemicals industry based on a mass comparison of tallow, palm and soy oil.

2.8 DETERMINE THE YIELD FACTOR FOR BIOFUEL CONVERSION

GREET reports system-level yield factors in pounds of bio-oil per pound of fuel for vegetable oil and high-FFA oils including tallow, UCO, and corn oil. We apply the inverse of these yield factors for our emission calculations. Tallow is another high-FFA oil, so we again apply a conversion rate of 0.91 for biodiesel and 0.85 for HVO on a kg fuel per kg feedstock basis.

2.9 PERFORM DISPLACEMENT EMISSIONS CALCULATION

Our final indirect estimates come out to 34.8 g CO₂e/MJ for tallow-derived biodiesel and 32.0 g CO₂e/MJ for tallow-derived HVO.

3. CASE STUDY 3: DISTILLERS CORN OIL (DCO)

3.1 DEFINE THE MATERIAL

Distillers corn oil is obtained from distillers grains by mechanical pressing or solvent extraction following the ethanol fermentation process. This material differs from edible corn oil which is pressed out of corn grain prior to fermentation. DCO has a higher FFA content than most vegetable oils, which can range up to 18 percent, and is considered more shelf-stable (Moreau & Hums, 2020; U.S. Grains Council, 2018).

DCO is already one of the primary biofuel feedstocks used in the U.S. and generates roughly a quarter of credits under the California LCFS (*California Air Resources Board Data Dashboard*, 2021).

3.2 ESTIMATE TOTAL SUPPLY AND SHARE OF USES IN EXISTING MARKETS

Approximately 860 kt of DCO is consumed in livestock feed today with the remainder used in the transportation market. If demand for DCO-derived biofuel increases, additional feedstock could be sourced from DDGS, another co-product of ethanol production.

To estimate total supply, we combine current DCO consumption in livestock feed with the maximum volume of additional DCO that could be extracted from oil embedded in DDGS. We thus include additional DCO that could potentially be produced, and not just the amount that is produced today. We determine the maximum quantity of DCO that can be extracted from a unit of DDGS from an experimental study by Singh and Cheryan (1998). Authors report this value to be approximately 66 milligrams corn oil extracted per gram of DDGS. We multiply this factor by the total volume of DDGS consumed in livestock feed today for a final estimate of 1,850 kt of additional DCO supply. Thus, we estimate that DCO supply could increase by more than double its current non-biofuel volumes.

3.3 DEFINE THE AMOUNT OF BIOFUEL

Combining the quantity of DCO used in livestock feed today and share of additional DCO embedded in DDGS that could be extracted following a strong policy signal, we estimate there is 92.3 PJ (2,700 kt) of divertable DCO supply that could be consumed in the biofuels sector. We set final biofuel demand at half this quantity, or 46.2 PJ (1,350 kt).

3.4 IDENTIFY SUBSTITUTE MATERIALS AND DETERMINE THE REPLACEMENT SHARE FOR EACH END USE

DCO is currently mixed into swine and poultry feed. Although DCO is not mixed into dairy and beef cattle feed, cattle do consume corn oil that has not been extracted and remains in the DDGS. Thus, we assume that DCO used for biofuel production that is diverted from existing DCO supply will be diverted from swine and poultry feed, while any additional DCO production will be diverted from cattle feed. As in the previous two case studies, we assume that beef and dairy cattle receive a grain substitute while swine and poultry receive an oil substitute when DCO is diverted from livestock feed. Since DCO is only fed to swine and poultry today, we assume that all feedstock diverted from animal feed will be replaced by low-cost soy oil.

For DCO embedded in DDGS, we look to the EPA's 2018 grain sorghum ruling as a precedent (Renewable Fuel Standard Program: Grain Sorghum Oil Pathway, 2018).

This rulemaking analyzed the indirect emissions impacts associated with sorghum oil extraction from DDGS. Citing the opinion of the US Department of Agriculture (USDA), EPA determined that corn will serve as a substitute material for sorghum oil extracted from DDGS. This is due to both its low-cost and available supply. We apply the same reasoning to DCO extracted from DDGS. We determine the substitution ratio based on the metabolizable energy content of DCO and corn.

3.5 DETERMINE THE ORDER OF DISPATCH

Supply of DCO exceeds biofuel demand, so not all DCO is diverted toward biofuel production in this case study. We assume that DCO fed directly to swine and poultry will be “dispatched” first and the remainder will be extracted from DDGS. As a sub-step, DCO is likelier to be extracted from DDGS fed to beef and dairy cattle than from swine and poultry diets. Because cattle do not consume high fat diets, we expect that these farmers would be more willing to purchase reduced-fat DDGS. DCO embedded in DDGS fed to swine and poultry is not extracted, since quantities from the prior two uses exceed the 46.2 PJ (1,353 kt) biofuel demand threshold. We include Table 2 below to illustrate our dispatch calculation:

Table 2. DCO order of dispatch by end use

End use	Consumption (kt)	Quantity diverted (kt)	Diversion ratio
Livestock feed (direct)	860	860	64%
Livestock feed (embedded in DDGS)	1,846	493	36%
Total	2,706	1,353	100%

3.6 IDENTIFY LIFE-CYCLE EMISSIONS FOR EACH SUBSTITUTE MATERIAL

We obtain LCA data for corn and soy oil from EPA’s GHG pathway emissions table.

3.7 DETERMINE THE SUBSTITUTION RATIO

For DCO diverted directly from poultry and swine feed, we assume that soy oil is substituted with DCO at a 1:1 ratio. Both oils have comparable nutritional value, so farmers are expected to replace diverted feedstock on a mass basis. For additional DCO that is extracted from DDGS fed to cattle, however, we expect farmers to replace diverted feedstock with corn on a metabolizable energy (ME) basis. We assume that reduced-oil DDGS is supplemented with corn to make up for lost calories from the extraction process. We source ME data for DDGS from INRAE-CIRAD-AFZ tables; we could not identify any ME data on DCO fed to ruminants, so we use soybean oil as a proxy. We estimate that for every kg of DCO extracted from DDGS fed to beef and dairy cattle, an additional 2.7 kg of corn is needed to supplement the lost calories in reduced-oil DDGS.

3.8 DETERMINE THE YIELD FACTOR FOR BIOFUEL CONVERSION

The FFA content of DCO sold on the market today can be as high as 18 percent (U.S. Grains Council, 2018), so we again select high-FFA yield factors from GREET for this feedstock. This corresponds to 0.91 for biodiesel and 0.85 for HVO on a kg fuel per kg feedstock basis.

3.9 PERFORM DISPLACEMENT EMISSIONS CALCULATION

Our final estimate for indirect displacement emissions is 26.9 g CO₂e/MJ for DCO-derived biodiesel and 24.8 g CO₂e/MJ for DCO-derived HVO.

4. CASE STUDY 4: PALM FATTY ACID DISTILLATES (PFADS)

4.1 DEFINE THE MATERIAL

PFADs are a by-product of the palm oil refining process and account for roughly 5 percent by weight (wt%) of crude palm oil output (Handojo et al., 2018). PFADs are formed during palm oil processing, when degraded material in palm fruit is converted to free fatty acids. PFADs are later removed from palm oil during the distillation process to increase its shelf life and improve its taste, odor and color (Neste, 2020). PFAD production is concentrated mainly in Malaysia and Indonesia, accounting for roughly 85% of global production (Malins, 2017). Since PFADs are not produced domestically in the U.S., we assume that increased biofuel demand in the U.S. will lead to feedstock diversion from global markets. Setting a global geographic boundary for our displacement analysis is unique to this feedstock.

4.2 ESTIMATE TOTAL SUPPLY AND SHARE OF USES IN EXISTING MARKETS

The total supply of PFADs worldwide is roughly 2,500 kt (Baldino et al., 2020); however, there is little data publicly available on the share of PFAD usage across end uses. Industry reports and the literature reveal that PFADs are used in livestock feed, oleochemicals production, and energy recovery at palm plantations (Cheah et al., n.d.).

We perform a “back of the envelope” calculation to determine the share of PFADs used in livestock feed today. Within the livestock industry, PFADs are primarily fed to dairy cattle to increase dietary fat content and milk yields (Palmquist, 2004). Hydrogenated PFADs may be fed directly to cattle, but more commonly, PFADs are used as an input for calcium salt production, also known as rumen protected fats (RPFs). RPFs are energy-dense feed supplements designed to bypass the rumen and aid digestibility (Hibma, 2010). RPFs can be made from a variety of FFA substances, although it is unclear how feedstock properties impact performance. RPF digestibility may increase with fatty acid chain length and degree of unsaturation, indicating that RPFs derived from soy oil would have an advantage over palm in ruminant diets (Naik, 2013). To its disadvantage, Sukhija and Palmquist report that unsaturated fats such as soy oil tend to dissociate at high rumen pH (Sukhija & Palmquist, 1990).

The global rumen-protected fat (RPF) market was valued at \$760 million in 2019 (Fior Markets, 2020). Assuming that the entirety of this market uses PFADs, the theoretical maximum, we can calculate the total volume of PFADs consumed by the livestock industry. Although we did not identify any market price information on RPFs, we doubled the estimate of the market value of palm oil, for a price of \$1400/tonne. For reference, the Federation of Oils, Fats, and Seeds Association (FOFSA) valued palm-derived fatty alcohols, another niche product, at \$1200/tonne in 2014. Using this data, we find that up to 530,000 tonnes of PFADs, or 21% of global production, may be used in RPF production consumed by the livestock sector. We assume the remainder is used in oleochemicals production and as a boiler fuel at the palm oil mill.

4.3 DEFINE THE AMOUNT OF BIOFUEL

The biofuel energy equivalent of global PFAD supply is approximately 87.6 PJ. We set biofuel demand at half of this value, or 43.8 PJ (1,250 kt).

4.4 IDENTIFY SUBSTITUTE MATERIALS AND DETERMINE THE REPLACEMENT SHARE FOR EACH END USE

Palm oil remains the lowest-cost oil alternative with elastic supply under global system boundaries (USDA Foreign Agricultural Service, 2021), so we assume it is the most likely marginal unit of replacement in the livestock sector. There is indication that there are already markets for rumen-protected fats made from palm oil in the U.S. In Colorado, the company Organilac produces RPF made with palm oil and whey protein. The company was approved for use in organic dairies across the U.S. in 2017 (Manriquez et al., 2019).

We also identify palm oil as the least cost oil substitute with elastic supply for the oleochemicals industry. Palm oil and PFADs share many of the same supply chains and palm is expected to remain the lowest-cost oil globally under steady demand (USDA Foreign Agricultural Service, 2021). Given the geographic scope of this case study, we assume all feedstock diverted from the oleochemicals sector will be replaced by palm oil.

In onsite energy recovery applications, heavy fuel oil will most likely serve as a boiler fuel replacement (Malins, 2017).

4.5 DETERMINE THE ORDER OF DISPATCH

Although all end uses have suitable replacement materials, we do not expect PFADs to be diverted from energy recovery applications. Local palm plantations that recycle PFADs as a boiler fuel are likely to be located in geographically isolated regions with a lack of existing supply chains. Therefore, we assume these plantation operators are equally unlikely to sell PFADs to biofuel markets.

Malins reports that PFAD supply chains in the livestock sector may be more diffuse than supply chains across the oleochemicals industry where markets are concentrated in Southeast Asia (2017). Although we could not obtain market data to support this claim, we assume that PFADs are more likely to be diverted from the oleochemicals sector. Due to the similar performance properties of vegetable oils in oleochemical applications, manufacturers have little preference for procuring PFADs relative to other fatty acid substances such as palm oil. PFADs have higher value in livestock feed applications where they are found to be more stable than palm oil-derived RPFs in acidic conditions (Megalac, n.d.). Since the share of PFADs used in the oleochemicals sector today exceeds the biofuel demand threshold, we assume that all PFADs are diverted from this end use.

4.6 IDENTIFY LIFE-CYCLE EMISSIONS FOR EACH SUBSTITUTE MATERIAL

Palm oil is the only substitute material identified for this feedstock. We source LCA data from EPA's GHG emissions pathways table.

4.7 DETERMINE THE SUBSTITUTION RATIO

We assume a 1:1 PFADs-to-palm substitution ratio in the oleochemicals sector using a mass-based comparison of both materials.

4.8 DETERMINE THE YIELD FACTOR FOR BIOFUEL CONVERSION

PFADs can be converted to both bio- and renewable diesel fuel; however, additional pretreatment demands during FAME processing make them likelier to be converted to HVO. We treat PFADs as another high-FFA oil, so we apply 0.91 biodiesel and 0.85 HVO conversion rates on a kg fuel per kg feedstock basis.

4.9 PERFORM DISPLACEMENT EMISSIONS CALCULATION

Our final indirect displacement emissions estimate is 48.7 g CO₂e/MJ for PFAD-derived biodiesel and 44.8 g CO₂e/MJ for PFAD-derived HVO.

5. CASE STUDY 5: MOLASSES

5.1 DEFINE THE MATERIAL

Molasses is a by-product of sugar refining produced from sugarcane and sugarbeet feedstocks. In the U.S., domestic molasses production is near evenly split between sugarcane in the South and sugarbeet in the Midwest (UDA ERS, 2021). Molasses products are generally designated with A, B, and C grades that reflect the level of distillation. Molasses A and B are typically used in food and feed products while Molasses C, or blackstrap molasses, containing the lowest sugar content is commonly used in bio-ethanol production. In our analysis, we assume all biofuel produced from molasses will be produced from Molasses C.

More so than any other feedstock assessed in this report, molasses could be considered a co- rather than by-product because it represents a greater share of the total value of its product chain. Molasses is roughly 15% the economic value of sugarcane and sugarbeet based on price data reported by the OECD-FAO (2019) and yield data reported by the International Sugar Association (2020). If molasses was designated as a co-product, a portion of upstream emissions from sugar refining including ILUC should be assigned to its feedstock carbon intensity (CI) score. California Air Resources Board (ARB) has classified molasses as a co-product and accordingly assigned upstream sugarcane production emissions to molasses biofuel pathways for the Low Carbon Fuel Standard (California Air Resources Board, 2019). However, for the purposes of our analysis, we assume that molasses is a by-product with inelastic supply.

5.2 ESTIMATE TOTAL SUPPLY AND SHARE OF USES IN EXISTING MARKETS

Baldino et al. report the domestic supply of Molasses C to be approximately 2,200 kt. Majority of the feedstock is consumed in livestock feed to improve palatability and increase the milk output of lactating dairy cows. Molasses has high calcium content to support milk production; molasses also serves as a nutrient source and binding agent in feed (El Takriti et al., 2017; Senthil Kumar et al., 2005). Outside the livestock sector, molasses can also be used as a substrate for the production of baker's yeast. Although available supply data on yeast production in the U.S. is outdated (Baldino et al., 2020), we assume demand in this sector has remained steady over time.

5.3 DEFINE THE AMOUNT OF BIOFUEL

We set molasses biofuel demand equal 10.3 PJ (1,110 kt), or half of available supply.

5.4 IDENTIFY SUBSTITUTE MATERIALS AND DETERMINE THE REPLACEMENT SHARE FOR EACH END USE

We identify several possible substitutes for Molasses C in the livestock feed and yeast production sectors. For dairy cows, we assume that all molasses is substituted with corn, a low-cost calorie substitute. In the Southern U.S., molasses could also be substituted with sugarcane juice due to its similar feedstock properties. However, due to a lack of information on sugarcane feed markets, we are not confident sugarcane juice would be widely available in locations where livestock feed is produced and thus exclude this substitute from our analysis. In addition to finding a calorie replacement, farmers may also look to replace the lost mineral content and binding properties from molasses diverted from feed. This could come in the form of vinasse, the material left

over after molasses fermentation in ethanol production. If molasses is diverted to ethanol production, the resulting vinasse could then be supplied to the same livestock feed producers that previously used the molasses. We find several examples of vinasse being used as a protein and mineral source in feed to aid digestibility (Bilal et al., 2001; Iranmehr et al., 2011). Although we typically exclude materials with inelastic supply from displacement analyses, any increase in molasses biofuel production will result in a corresponding increase in vinasse production, which delivers the same mineral content as the molasses would have in livestock feed. Thus, we assume vinasse consumption is associated with zero upstream emissions impacts.

In addition to livestock feed, molasses is used to a lesser degree in baker's yeast production. Yeast requires a sugar substrate, nitrogen and other minerals to form under controlled conditions (Lallemand Inc., 2018). In the EU, molasses makes up more than 90% of the sugar substrate used by the yeast industry, with the remainder sourced from glucose syrups (El Takriti et al., 2017). We found relatively little data on yeast production in the U.S., but assume molasses also serves as the predominant yeast substrate. Raw juice extracted from sugarcane or sugarbeet is a possible substitute for molasses diverted from baker's yeast production. El Takriti et al. assume these juices replace molasses diverted from the yeast sector in their analysis of indirect emissions from molasses in the EU. However, this assumption was made partly due to a lack of data on glucose syrup origins and their associated GHG emissions (2017).

Spigno et al. propose that corn glucose syrup combined with corn steep could be used as another possible substitute (Giorgia Spigno et al., 2009). Corn glucose syrup acts as a sugar source while the high nitrogen content of corn steep, a by-product of corn wet milling, facilitates yeast growth. Since the nitrogen content of molasses is relatively low, molasses must be also be supplemented with nitrogen compounds, phosphate and other minerals to facilitate yeast production (Lallemand Inc., 2018). Considering that additional nutrients are added for both primary and substitute feedstocks, we exclude the upstream emissions from corn steep production in our analysis.

In the U.S. context, corn glucose syrup is the likeliest sugar substitute for the baker's yeast industry. We do not identify any market data for sugarcane and sugarbeet juice production; thus, these products are likely not available in large quantities domestically. Corn glucose syrup is produced from an abundant U.S. feedstock, corn, with production and cost data tracked annually by the USDA.

5.5 DETERMINE THE ORDER OF DISPATCH

Corn is cheaper than the energy equivalent quantity of molasses in feed; thus, we assume molasses is diverted from the livestock sector first. The average wholesale price of corn grain was 144 USD per tonne in 2019 (*USDA ERS - Feed Grains Database*, n.d.). We do not have current information on U.S. molasses prices, so we source the latest cost data reported by the USDA Economic Research Service (ERS) from 2014. Adjusting for inflation, the wholesale price of molasses comes out to roughly 172 USD per tonne today, roughly 20% greater than its material substitute. Although there is economic incentive to replace molasses with corn regardless of U.S. biofuels demand, molasses has historically been fed to dairy cattle to improve palatability.

Molasses diversion from baker's yeast production occurs next. The substitute material we identify, corn glucose syrup, is significantly more expensive than corn due to the extra processing stages needed to convert starch to glucose. The average wholesale price of corn syrup was more than 5 times that of corn grain in 2019 (*USDA ERS - Sugar*

and *Sweeteners Yearbook Tables*, n.d.). In addition to substitutes likely being cost-prohibitive, diverting additional molasses volumes exceeds the 50% biofuel demand threshold, so we exclude molasses diversion from this end use from our analysis.

5.6 IDENTIFY LIFE-CYCLE EMISSIONS FOR EACH SUBSTITUTE MATERIAL

Upstream emissions associated with corn production are sourced from EPA's GHG pathways emission table. We find emissions data on corn syrup production from a report by Renouf et al (2008). The life-cycle emissions for corn syrup are substantially higher than corn due to the energy-intensive conversion process to convert starch to glucose. As discussed in Section 5.4, we attribute vinasse substitution with zero indirect emissions impacts.

5.7 DETERMINE THE SUBSTITUTION RATIO

To determine the substitution ratios in livestock feed, we again reference metabolizable energy content data from the INRAE-CIRAD-AFZ feed tables. Molasses has a lower ME than corn, so quantities diverted from livestock feed are replaced with a lesser quantity of corn. This relationship comes out to 0.73 kg corn for every 1 kg of molasses diverted. Although the ME of sugarcane and sugarbeet molasses differ slightly, the substitution ratio is based on their average ME as production volumes are roughly split between the two feedstocks in the U.S. Vinasse has a similar nutritional composition to molasses and can also serve as a feed binding agent; previous research has found can be used to replace molasses in a 1:1 ratio in ruminant diets (Hidalgo, 2009).-

5.8 DETERMINE THE YIELD FACTOR FOR BIOFUEL CONVERSION

Due to its sugar content, the final biofuel product produced from molasses feedstock is ethanol. GREET does not report yield data for this biofuel pathway, so we source yield estimates from a study by Liang et al. (2008). Converting estimates to kg fuel per kg feedstock, we apply a final yield factor of 0.35 in our analysis.

5.9 PERFORM DISPLACEMENT EMISSIONS CALCULATION

Our final estimate for indirect displacement emissions is 32.9 g CO₂e/MJ for molasses-derived ethanol.

6. CASE STUDY 6: SAWMILL RESIDUES

6.1 DEFINE THE MATERIAL

Sawmill residues are a relatively low-value by-product of the sawmill industry. These materials include sawdust and cutter shavings produced during sawing operations that are often consumed onsite or close to their point of origin.

6.2 ESTIMATE TOTAL SUPPLY AND SHARE OF USES IN EXISTING MARKETS

Baldino et al. estimate the total supply of sawmill residues in the U.S. to be 64,000 kt, drawing upon data from the USDA Forest Service (2018). Total production has declined over the last three decades; however, it is unclear whether this trend will continue (Baldino et al., 2020). Sawmill residues can be recycled for energy recovery at lumber mills and paper and pulping plants. Residues are also used in a variety of consumer fiber products such as oriented strand board (OSB) and particle board. Other applications of this material include animal bedding, mulch, and niche consumer products such as decorative bark (Baldino et al., 2020). As of 2016, roughly half of sawmill residues were used in fiber and other miscellaneous products while the remaining half was used as a boiler fuel.

6.3 DEFINE THE AMOUNT OF BIOFUEL

There is ample supply of sawmill residues in the U.S. We set demand at 50% of total supply, or 219 PJ (32,000 kt).

6.4 IDENTIFY SUBSTITUTE MATERIALS AND DETERMINE THE REPLACEMENT SHARE FOR EACH END USE

We expect that sawdust and cutter shavings are replaced with a low-cost fuel source in industrial boiler applications. We draw data from a report by Puettmann and Lippke (2012) to estimate the share of energy consumption by fuel type at U.S. sawmills. Authors conducted an LCA of a typical U.S. softwood lumbermill where 50% of heat generation was met by woody biomass while the remaining half of generation was met by natural gas. Wood-fired boilers are common at lumbermills with available biomass supply including sawdust, shavings, and trimmings. At facilities producing secondary fiber products such as laminated veneer lumber (LVL) and fiberboard, natural gas is a more common fuel substitute (M. E. Puettmann & Milota, 2017).

We assume that sawmill residues are likely to be replaced by low-cost biomass feedstocks in older boiler units. Pulpwood, or raw trees logged for the paper industry, is selected as the most likely replacement. Given the current share of fuel usage at paper mills in the U.S., we assume natural gas and pulpwood are equally likely to replace sawmill residues in this application. For comparison, Malins calculated a 0.57:0.43 biomass to natural gas split for industrial boiler substitutes in a displacement analysis for sawmill residues in Europe (2017). In that study, short-rotation willow and miscanthus were identified as likely substitutes for boiler fuel; however, in North American markets, pulpwood is more widely available.

A 1:1 replacement share for both industrial boiler substitutes is also justifiable from an economic standpoint. In 2020, wholesale natural gas prices ranged between 2-3 USD/MMBTU (Energy Information Authority, 2021), comparable to the latest available pulpwood prices. Although economic data for pulpwood is not tracked as regularly,

a recent consultancy study reported pulpwood costs were approximately 2 USD per MMBTU in 2017 (Forest2Market Inc, 2018). Considering that natural gas boilers have a roughly 10% combustion efficiency advantage over biomass boilers, the costs per unit of thermal energy delivered for both feedstocks are expected to even out. Efficiency losses are due to biomass' higher moisture content.

Within the fiber products sector, sawmill residues could be replaced by additional woody biomass or straw for use in construction materials or plastic such as polypropylene in furniture production. The cost of polypropylene is approximately 9 times that of OSB on a unit tonne basis (*Global Polypropylene Prices 2021*, n.d.), so we do not consider this material to be a viable substitute. We estimate OSB prices based on the cost of OSB per cubic meter reported by the USDA and density of the material in the U.S. reported by the Food and Agricultural Organization (FAO) (Brandeis et al., 2021; FAO et al., 2020). In the U.S., straw is not widely used as an input for fiber products production so we assume that all substitute materials will be sourced from woody biomass. To avoid secondary displacement calculations, we select pulpwood is the least-cost replacement with elastic supply.

6.5 DETERMINE THE ORDER OF DISPATCH

There are no technical barriers to feedstock substitution in either the fiber products industry or in energy recovery at paper and pulping (PNP) PNP plants. Additionally, all substitutes have comparable costs; pulpwood is identified as a substitute for both end uses and its costs are roughly equivalent to the wholesale price of natural gas. Thus, we assume there is no prioritization for diverting from either end use. In our dispatch calculations, we weight both sectors equally up to the 219 PJ biofuel demand threshold.

6.6 IDENTIFY LIFE-CYCLE EMISSIONS FOR EACH SUBSTITUTE MATERIAL

The life-cycle emissions for natural gas are drawn from GREET including upstream production emissions and combustion emissions in industrial boiler applications. GREET does not report LCA data for pulpwood, so we draw upon a study on carbon payback periods for softwood in the Southeastern U.S. (Jonker et al., 2014). Jonker et al. report data on forest biomass yield and the carbon debt between baseline forest and low-productivity harvesting scenarios, Assuming that trees are harvested from temperate forests, and using a standard conversion factor of 0.47 tonnes of carbon per tonne of forest biomass, we calculate the CI for pulpwood to be 70.6 g CO₂e/MJ. We choose the low-productivity scenario to be consistent with evidence presented in Giuntoli & Searle (2019) that bioenergy demand does not substantially increase pulpwood productivity in the Southeastern U.S. We apply a 30% uncertainty range to our pulpwood production CI estimate.

6.7 DETERMINE THE SUBSTITUTION RATIO

The substitution ratio for natural gas relative to sawmill residues is based on each fuel's specific energy and combustion efficiency in industrial boilers. Natural gas has a significantly higher lower heating value (LHV) than sawmill residues so every kg of diverted feedstock must only be replaced with 0.37 kg of substitute material to achieve the same thermal energy output, accounting for differences in boiler conversion efficiencies. Pulpwood has a comparable LHV to sawmill residues, so we assume a 1:1 substitution ratio on a mass basis for this substitute.

For the fiber products sector, we assume that pulpwood replaces sawmill residues on a 1:1 basis. Both feedstocks are sourced from the same biomass material, so we calculate this ratio on a mass basis.

6.8 DETERMINE THE YIELD FACTOR FOR BIOFUEL CONVERSION

Sawmill residues have high lignin and hemicellulose content and can be converted to biofuel via fermentation or Fischer-Tropsch synthesis. Both conversion processes are relatively inefficient due to pretreatment demands and the high moisture content of woody biomass. Using data from GREET, we calculate cellulosic ethanol yield to be 0.25 kg fuel per kg feedstock while the yield for FT-diesel is 0.15 kg fuel per kg feedstock.

6.9 PERFORM DISPLACEMENT EMISSIONS CALCULATION

Our final estimate for indirect displacement emissions is 171.3 g CO₂e/MJ for sawmill residues-derived ethanol and 175.6 g CO₂e/MJ for sawmill residues-derived Fischer-Tropsch (FT) diesel.

7. CASE STUDY 7: CRUDE TALL OIL (CTO)

7.1 DEFINE THE MATERIAL

Crude tall oil is among the many by-products of the paper and pulping industry. Also known as pine chemicals, these derivatives have high oil and fatty acid content and are used in a variety of consumer products. CTO is produced from a multi-step process. During the Kraft pulping process, the lignin content of wood is separated from cellulose fiber by mixing wood chips with salt compounds under high pressure. Following this treatment, spent cooking fluid, known as black liquor, contains all the lignin content of wood plus resin and fatty acids converted to sodium salts. These salts and other non-soluble compounds, known as black liquor soap (BLS), naturally separate from the black liquor and form a stable foam that can be skimmed off the top of black liquor (Harding & Hendrickson, 1964). BLS can be later acidulated to form CTO and CTO later fractionated to form higher value distillation products (Cashman et al., 2016).

7.2 ESTIMATE TOTAL SUPPLY AND SHARE OF USES IN EXISTING MARKETS

CTO is used in numerous applications throughout the U.S. including onsite energy generation at paper and pulping mills, as an additive for oil drilling, and in a variety of consumer products such as adhesives, inks, rubbers, and plastics (Cashman et al., 2016; Malins, 2017). Total supply of CTO is roughly 775 kt and is expected to increase in the future. Aryan and Kraft estimate that North American CTO production could increase up to 30% between 2018 and 2030 (2021). That study expects this growth could come from a combination of increases in BLS acidulation and growth in total pulp production. Using data from Aryan and Kraft, we determine that only 5% of the projected increase in CTO production will come from increased acidulation with the remainder from increased pulp production.

The breakdown on how CTO is used within different industries across the U.S. is not publicly tracked. Pavlenko et al. (2020) calculated the share of CTO used in different end uses, drawing upon numerous sources from the literature (Aryan & Kraft, 2021; Baldino et al., 2020; Peters & Stojcheva, 2017). Approximately 60% of CTO is used in distillation products, or pine chemicals; 3% as boiler fuel at PNP plants; 7% as an additive for petroleum drilling; and the remainder is exported. We exclude exported shares from our analysis, so adjusted supply volumes are presented in Table 3 below.

Table 3. U.S. CTO consumption by end use

End use	Feedstock supply (kt)	Biofuel supply (PJ)	% total supply
Energy recovery	31	1.2	8%
Drilling	72	2.8	19%
Increased acidulation	43	1.7	11%
Distillation products	627	9.4	62%
Total	773	15.1	100%

7.3 DEFINE THE AMOUNT OF BIOFUEL

We estimate that approximately 15 PJ (387 kt) of CTO could be diverted to biofuel, or half of total supply.

7.4 IDENTIFY SUBSTITUTE MATERIALS AND DETERMINE THE REPLACEMENT SHARE FOR EACH END USE

There are numerous substitutes for CTO across its existing uses. Like sawmill residues, CTO recycled as boiler fuel at paper and pulping (PNP) plants is likely to be replaced by natural gas and pulpwood. Natural gas is also expected to serve as a fuel replacement in more modern boilers while pulpwood replaces CTO in older biomass boilers. Peters and Stojcheva identified heavy fuel oil as another possible boiler fuel replacement at PNP plants; however, fuel oil is nearly three times the cost of natural gas on a per MMBTU basis (U.S. EIA, 2021) and, more recently, fuel oil boilers have been phased out in favor of natural gas and biomass alternatives (Bhander & Jozewicz, 2017).

Natural gas has a slightly higher cost per MMBTU than harvested pulpwood but also burns at a higher combustion efficiency. Expanded CTO production via increased acidulation will also reduce the quantities of its precursor material, BLS. BLS is also used in onsite energy recovery at pulping mills, so additional replacement fuels would be needed for this application. As with CTO, we expect that BLS diverted from onsite energy recovery will be replaced by a 50:50 split between natural gas and pulpwood.

In the drilling industry, CTO is used as an additive for petroleum extraction. This process utilizes a variety of different chemicals under pressurized conditions to extract petroleum embedded in underground wells. Although water-based solutions are more widely used, oil-based drilling fluid or “mud” can extract petroleum from high temperature wells and geological areas prone to swelling (Anderson et al., 2010). We assume that crude petroleum will replace CTO as an oil-based substrate in drilling applications.

The remainder of CTO used in biofuels production will be diverted from the pine chemicals industry. To identify substitutes and substitute replacement shares for these products, we draw upon a report by Cashman et al. (2016). This report includes a detailed overview of CTO distillation products, their market share, expected substitutes, and in cases where there are multiple substitutes, the market share of each substitute. We apply the same assumptions in our analysis with the exception of tall oil heads and pitch. Here, we assume natural gas is used in place of fuel oil in industrial boiler applications. A complete list of CTO substitutes and their expected share of displacement is included in Table 4 below.

Table 4. CTO distillation product substitutes and estimated replacement share

CTO distillation products	End use	Substitute	Substitute market share, %	Share of distillation product replacement, %
Heads	Energy recovery	Natural gas	100%	6.5%
Pitch	Energy recovery	Natural gas	100%	16.0%
Tall oil rosin	Paper	ASA	90%	11.5%
	Paper	Gum rosin	10%	1.3%
	Rubber	C5 Hydrocarbons	100%	2.8%
Rosin ester	Adhesives	Gum rosin ester	20%	1.1%
	Adhesives	C5 Hydrocarbons	80%	4.5%
	Ink	Acrylic resin	100%	12.8%
Tall oil fatty acid	Surfactants, paints, oilfield chemicals	Soybean oil	100%	38.0%
Distilled tall oil	Paints	Soybean oil	100%	1.8%
	Surfactants	Soybean oil	100%	1.8%
	Rubber	C5 Hydrocarbons	100%	1.8%

7.5 DETERMINE THE ORDER OF DISPATCH

We assume CTO is first diverted from energy recovery applications and replaced with natural gas and pulpwood. Both fuel alternatives are available at a lower cost than the diverted feedstock. We could not find any data on current crude tall oil prices in the U.S.; therefore, we reference Peters and Stojcheva for historic CTO prices in the European market. Adjusting data for price inflation, CTO was valued at 13 USD/MMBTU in 2013. We also calculate a negative cost differential between CTO and crude petroleum used in drilling applications. The average wholesale spot price of crude petroleum reported by the US Energy Information Authority (EIA) in 2021 is roughly 11 USD/MMBTU.

The remainder of CTO used in biofuels production will be diverted from the pine chemicals industry. Globally, the US produces the highest quality CTO on the market due to its high rosin acid content sourced from softwood pine (Peters & Stojcheva, 2017). Although several material substitutes exist, we assume that CTO will be least likely to be diverted from these niche product applications Under the highest demand threshold, approximately 62% of distillation products are kept in their existing end uses.

7.6 IDENTIFY LIFE-CYCLE EMISSIONS FOR EACH SUBSTITUTE MATERIAL

- » Life-cycle emissions for substitute materials are largely drawn from an in-depth LCA of CTO and its substitutes (Cashman et al., 2016). Authors report the carbon intensity for each pine chemical substitute in kg CO₂e per kg material.
- » For the drilling sector, life-cycle emissions for crude petroleum are fairly low. Petroleum is not combusted during the drilling process and we do not find any research indicating that petroleum degradation during spent drilling fluid disposal releases any fugitive carbon emissions (Ramirez, 2009). Thus, we only include the upstream emissions from petroleum extraction in our analysis. However, we do add an additional emissions factor to account for CTO biofuel combustion. Although CTO combustion is biogenic, and often treated as having zero carbon emissions, it releases additional emissions relative to the counterfactual scenario where CTO is sequestered underground following drilling.

» Upstream emissions for natural gas and pulpwood are sourced from GREET and Jonker et al., respectively. See Case Study 6 for a more detailed explanation of these assumptions.

7.7 DETERMINE THE SUBSTITUTION RATIO

Within the distillation sector, we determine a substitution ratio based on the physical density of products. With the exception of tall oil heads and pitch burned for energy recovery, we assume a 1:1 ratio for substitute materials. In drilling applications, we base the substitution ratio on a volume basis using the mass density of fluids. Tall oil is more dense than crude petroleum, so its substitution ratio (kg substitute/kg feedstock) is slightly greater than 1.

For energy recovery applications including increased acidulation, we calculate the substitution ratio based on the specific energy of fuel, adjusted for combustion efficiency in industrial boilers.

7.8 DETERMINE THE YIELD FACTOR FOR BIOFUEL CONVERSION

We assume that CTO will be converted to renewable diesel, or HVO, or jet fuel via the HEFA process. There is one facility in Finland currently producing renewable diesel derived from CTO today (Malins, 2017). Tall oil has high free fatty acid content (Mikulec et al., 2012), so we source yield data for this category from GREET. Our final yield estimate is 0.85 kg HVO per kg of CTO.

7.9 PERFORM DISPLACEMENT EMISSIONS CALCULATION

Our final estimate for indirect displacement emissions is 58.7 g CO₂e/MJ for CTO-derived HVO.

8. CASE STUDY 8: MANURE

8.1 DEFINE THE MATERIAL

Manure is animal excrement sourced from livestock farms across the U.S. Dairy cattle and swine produce the highest quantities of manure while poultry account for only a small share of manure production (Lorimor et al., 2004). The high nitrogen content in poultry manure inhibits biogas production (Einarsson & Persson, 2017), so we exclude these quantities from our analysis.

8.2 ESTIMATE TOTAL SUPPLY AND SHARE OF USES IN EXISTING MARKETS

It is difficult to obtain an accurate estimate of manure supply in the U.S., but we know that it is large. The U.S. Department of Energy (DOE) estimates that 37 million dry tonnes of manure are recoverable (2017), of which 33% is applied as fertilizer, 3% is used for the production of biogas that is then combusted in heat and power production, and the remainder is managed in various storage applications. These include anaerobic lagoons, deep pits, solid storage, and spread on fields and pastures for disposal (U.S. Environmental Protection Agency, 2018). The IPCC has published detailed definitions for manure management systems which we adapt in Table 5 below.

Table 5. Manure management system definitions (adapted from IPCC, 2006)

Management System	Definition
Anaerobic lagoon	Liquid storage system designed for waste stabilization. Storage periods may be longer than 1 year
Daily spread	Manure routinely removed from confined facility and applied to cropland or pasture within 24 hours of excretion
Deep pit	Manure storage under slatted floors in animal housing
Solid Storage	Dry manure storage in unconfined piles or stacks. Storage period lasts several months
Liquid/slurry	Manure stored as excreted or with minimal addition of water in tanks or earthen ponds outside animal housing. Storage period typically lasts less than 1 year
Pasture	Unmanaged manure deposited from pasture and range-grazing animals

Detailed data on manure management systems by state is tracked by the joint U.S. EPA-USDA AgStar program. A breakdown of non-digester manure applications by livestock type is provided in Figure 2 below. The left-hand graphic presents the share of manure management systems used for swine while the right-hand graphic presents the share of manure management systems used for dairy cattle.

For manure that is anaerobically treated in digesters and converted to biogas, the AgStar program has also compiled a database of manure operating facilities and associated biogas output (US EPA, 2014). Using this data we find that roughly 72% of manure biogas is used in heating applications while the remainder is used to generate electricity.

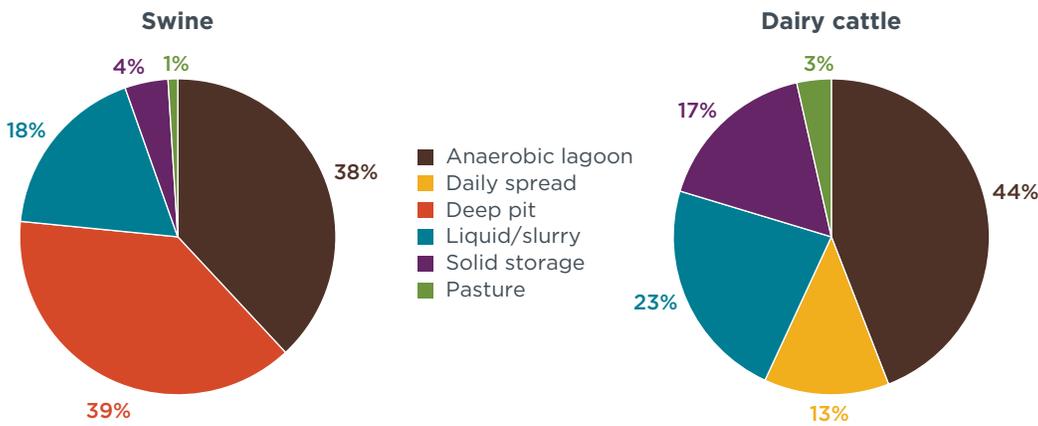


Figure 2. Left: U.S. manure application by management system (swine). Right: U.S. manure application by management system (dairy cattle)

8.3 DEFINE THE AMOUNT OF BIOFUEL

We set demand for manure-derived biogas equal to half of total supply, or 121 PJ (120 billion ft³).

8.4 IDENTIFY SUBSTITUTE MATERIALS AND DETERMINE THE REPLACEMENT SHARE FOR EACH END USE

In anaerobic digesters, microbes break down the organic compounds in manure, converting it to biogas. Biogas can then be compressed and treated and used as a heat and power source.

Biogas diverted from heating applications including boilers and cogeneration can be substituted with low-cost natural gas. Once biogas is cleaned of contaminants and upgraded, the resulting biomethane is a highly compatible replacement fuel. Though biogas has a lower energy density than natural gas, *biomethane* is interchangeable with natural gas on an energy basis. For biogas diverted from electricity generation, we assume grid electricity will serve as the likeliest substitute.

Manure applied as a fertilizer at nearby crop farms could be replaced with either synthetic fertilizer or digestate, a solid by-product of anaerobic digestion left over when organic matter is converted to biogas (Möller & Müller, 2012). Möller and Müller summarize research on the nutrient properties of this residue, finding there to be no significant differences between nutrient content and uptake efficiency between digestate and liquid cow and pig manure in field applications. Since digestate is widely available to livestock and crop farmers at no additional cost, we assume that farmers are more likely to utilize digestate than to purchase synthetic fertilizer to serve as a nutrient replacement.

Synthetic fertilizer has a much higher concentration of nutrients per kg than organic alternatives and may be preferable when digestate is not available. Synthetic fertilizer production is emissions-intensive but its emissions footprint is mitigated due to its very low substitution ratio. For example, we calculate that only .08 kg of urea is required to replace the nitrogen content in a kg of diverted manure. Overall, if farmers were to purchase synthetic fertilizer, this would raise displacement emissions tremendously. Further research is needed to determine the likelihood of farmers purchasing synthetic fertilizer in place of digestate to narrow the range of indirect emissions effects.

Finally, manure that is currently not being put to productive use and stored in anaerobic lagoons or other waste applications will not require any material substitutes. Manure releases high quantities of methane in these applications so diverting the feedstock toward biofuels production will result in a negative displacement effect.

We do not have complete information on the share of manure currently applied as fertilizer vs. the share left to decompose organically in storage across the different management systems. Therefore, we assume that manure is equally likely to be replaced with digestate or result in negative displacement emissions.

8.5 DETERMINE THE ORDER OF DISPATCH

We assume manure converted to biogas for heat and power production at livestock facilities is the first end use displaced. These facilities are already equipped with the infrastructure to produce digester biogas and would only require the addition of a biogas upgrading system to deliver biofuel to the transportation sector. For the feedstock's remaining end uses, livestock facilities would need to invest in capital equipment including pumps and digesters to convert manure to biogas and later upgrade biogas for use in the transportation sector.

Livestock facilities that process large volumes of manure waste are the next likeliest to be dispatched. Due to the high biogas potential from manure stored at these locations, it is more economical to build biogas digesters at these sites than small-scale facilities employing dry or "solid storage" management. Large-scale facilities are likely to use wet storage management practices including anaerobic digestion and liquid/slurry systems (U.S. Environmental Protection Agency, 2018).

The last end use to be dispatched is manure used in deep pit and dry management systems. In an analysis of biogas recovery potential of the U.S. agriculture sector, EPA finds that deep pit storage sites would require both capital upgrades and changes in handling practices making them an unsuitable candidate for biogas recovery.

8.6 IDENTIFY LIFE-CYCLE EMISSIONS FOR EACH SUBSTITUTE MATERIAL

The life-cycle emissions for manure substitutes include grid electricity, natural gas, synthetic fertilizer and digestate. We use data from EPA's Emissions & Generation Resource Integrated Database (eGRID) for average carbon intensity factors for the U.S. electric grid. Natural gas upstream and combustion emissions are drawn from GREET while digestate is a waste material allocated with no feedstock emissions. Calculating the life-cycle emissions for synthetic fertilizer and avoided methane require more detailed calculations.

Fertilizer is comprised of three essential nutrient components: nitrogen, phosphate, and potassium. While organic sources of fertilizer contain all three nutrients, synthetic fertilizer can be sold as a combination of all three or sold as one nutrient source in high concentrations. Urea is the most common nitrogen-based fertilizer, potash fertilizer is high in potassium, and triple super phosphate is rich in phosphate. We source data on the production emissions associated with each nutrient-specific fertilizer from a project commissioned by the European Commission (2017).

Finally, manure diverted from waste management applications would result in a negative displacement effect. We calculate this effect based on IPCC methane emissions formulas (2006). In IPCC guidance, emissions formation factors vary widely

by livestock type and management system. We also obtain data on the average quantity of manure produced by each class of livestock animal (Lorimor et al., 2004). From this data, we can estimate the annual share of manure produced by each livestock type. We then multiply these values by the species-specific emission factors from IPCC documentation to determine the quantity of emissions released per kg of manure stored in non-digester end uses. We estimate displacement emissions for this end use to be $-0.24 \text{ kg CO}_2\text{e}$ avoided per kg of diverted manure for wet storage applications and $-0.02 \text{ kg CO}_2\text{e}$ avoided per kg of diverted manure for dry storage applications.

8.7 DETERMINE THE SUBSTITUTION RATIO

Manure is not directly burned to generate electricity, so we determine the electricity substitution ratio based on the kilowatt-hours (kWh) of electricity produced per volume of manure-biogas. We source performance data from EPA's AgStar database and apply an additional 65% conversion efficiency factor. In total, we estimate that roughly 2 kWh of electricity is produced per cubic meter of biogas. We multiply this value by the expected volume of biogas produced per kg of digested manure from GREET. In sum, we calculate a substitution ratio of 0.36 kWh purchased electricity per kg diverted manure.

The AgStar database reports that more than 98% of thermal energy from manure biogas is used in cogeneration systems with the remainder burned as boiler fuel. Thus, we calculate the natural gas:manure substitution ratio based off feedstock performance in cogeneration systems. Unlike boiler systems, the combustion efficiency of cogeneration or combined heat-and-power (CHP) systems is roughly equivalent when run on either natural gas or biogas. Thus, we determine the substitution ratio for thermal energy applications based solely on the biogas production rate per kg of feedstock.

For fertilizer, we calculate the substitution ratio based on the nutrient content in dry weight percentage for manure and synthetic materials. Synthetic fertilizers such as urea are much more concentrated, so although their LCA emissions are high, they can be applied at much smaller quantities than manure. We determine the substitution ratio using data from Geng et al. (2019). In this report, authors investigated the effect different fertilizers had on crop growth when organic material was replaced with synthetic compounds. Nutrient data was reported on a percentage wet matter basis which we convert to dry matter. From there, we can compare the nutrient concentration of organic manure relative to the nutrient concentration of synthetic fertilizer given in VegaAlga project documentation (European Commission, 2017).

We multiply production emissions for each type of fertilizer by their respective substitution ratio to determine the total substitution emissions associated with diverting one unit of feedstock toward the biofuels sector. In total, we calculate substitution emissions at $.82 \text{ kg CO}_2\text{e}$ per kg manure diverted.

8.8 DETERMINE THE YIELD FACTOR FOR BIOFUEL CONVERSION

We assume manure is digested, processed, and upgraded to pipeline-grade biogas fuel, also known as renewable natural gas (RNG). We source biogas production data from GREET, assuming the median volatile solid reduction (VSR) rate in anaerobic digesters. GREET also reports livestock-specific volatile solids (VS) to total solids (TS) ratios to calculate yield factors. We weight these ratios by the share of manure produced by each livestock type and for an average 0.55 kg VS/kg TS conversion rate.

Multiplying the two terms together, we estimate a yield of 0.18 kg biogas per kg of manure, one of the lowest yields of all feedstocks studied.

8.9 PERFORM DISPLACEMENT EMISSIONS CALCULATION

Our final estimate for indirect displacement emissions from manure-derived biogas is between -35.9 and 118 g CO₂e/MJ. The high estimate assumes manure applied as fertilizer is entirely replaced by synthetic material while the low estimate assumes these quantities are entirely replaced by digestate. We select the lower bound as our central emissions estimate, given that digestate can serve as a fertilizer replacement in most to all applications. Determining a more accurate share of digestate vs. synthetic fertilizer replacement would reduce uncertainty in our range of indirect emissions calculations.

9. CASE STUDY 9: FOOD WASTE

9.1 DEFINE THE MATERIAL

Approximately 30% of all food supply in the U.S. is wasted (U.S. Department of Agriculture, 2021). Waste occurs at both the household and commercial levels due to spoilage or damage. While food can be wasted along the transport supply chain, most waste occurs when consumers purchase quantities of food that exceed their demand. Relative to other organic materials, food waste is high in moisture content and is associated with high rates of methane production in an anaerobic environment (Banks et al., 2018).

9.2 ESTIMATE TOTAL SUPPLY AND SHARE OF USES IN EXISTING MARKETS

Estimates for the total supply of food waste in the U.S. vary. Beginning in 2018, EPA expanded its tracking of food waste management data which we use to determine the share of food waste used in various end-use applications (US EPA, 2017). EPA reports that approximately 70% of food waste is sent to landfills today. A much smaller share is anaerobically digested and converted to biogas for heat and power applications. Food waste can also be combusted directly with other municipal solid waste (MSW) materials to generate electricity. Approximately 15% of all food waste is burned directly in these waste-to-energy applications. Food waste can also be composted, donated, or used in various other material applications (US EPA, 2017). In total, EPA estimates that 11.8 million dry tonnes of food waste were produced in the U.S. in 2017.

9.3 DEFINE THE AMOUNT OF BIOFUEL

The potential supply of food waste biogas is roughly 128 PJ, so we set biofuel demand equal to half that value, or 67.1 PJ (66 billion ft³).

9.4 IDENTIFY SUBSTITUTE MATERIALS AND DETERMINE THE REPLACEMENT SHARE FOR EACH END USE

We assume that food waste used in compost has no suitable replacement materials. Unlike fertilizer, compost is not primarily used for growing crops but as a soil amendment in smaller applications such as mushroom cultivation and urban farming (van Veenhuizen, 2006). In composting applications, food waste is used for its high moisture content rather than its nutrient properties.

Incinerators or waste-to-energy (WTE) plants are already connected to local electric grids, so a reduction in output due to FW diversion will be compensated by an increase in electricity generation elsewhere within the grid. Thus, we assume that FW is replaced by grid electricity in WTE applications.

Consistent with other feedstocks, we assume FW is replaced with natural gas and grid electricity in heat and power applications, respectively. However, we assume that both the electricity and heat output from cogeneration systems are replaced by natural gas.

We do not have complete data on the share of heat and power production at co-digestion facilities, so we estimate substitute replacement shares based on survey data of roughly 150 FW processing facilities in the U.S. (Pennington, 2018). Facility operators self-reported their total volumes of waste processed and the various biogas end-use applications including boiler fuel, combined heat and power, and electricity generation. Across all digester types, we estimate that approximately 37% of biogas

produced from FW co-digestion is used in electricity applications while 63% is used in heating applications. These estimates are fairly consistent with the share of energy produced from manure digestion reported in the AgStar database.

We assume that landfilled FW diverted to biofuels production has a negative displacement effect due to methane release under the counterfactual scenario. We consider landfilled FW to be a strict waste product requiring no substitute materials.

9.5 DETERMINE THE ORDER OF DISPATCH

As with manure, we assume that food waste already sorted and processed in anaerobic digesters is the most likely diversion application. Facilities already processing biogas would require significantly less capital investment to upgrade biogas to pipegrade quality. Once all FW is diverted from anaerobic digestion, we assume that the remainder is diverted from landfills. Diversion from this sector is associated with negative displacement emissions from avoided methane release during organic material decomposition. We prioritize waste incineration later in the order of dispatch due to the operating challenges associated with FW diversion. WTE operators are dependent on a steady stream of combined MSW material. If smaller volumes of waste were delivered due to FW diversion, this would impact generator uptime and overall efficiency of the plant. Landfill operations are much less dependent on the volumes of waste delivered. Additionally, diverting FW from landfills would cost no more to operators than the loss of tipping fees since this end use requires no substitutes.

Food waste used in composting applications is also expected to remain in its existing end use, since we identify no likely substitute materials.

9.6 IDENTIFY LIFE-CYCLE EMISSIONS FOR EACH SUBSTITUTE MATERIAL

As in the manure biogas case study, we source natural gas CI factors from GREET and U.S. grid-average electricity emission factors from the eGRID database. The nationwide grid-electricity CI score will decrease in coming years as more renewable resources are brought online, so displacement emissions for this feedstock will likely decrease in the future.

We draw data on the rate of methane release per tonne of waste from uncovered and covered landfills from the EPA Waste Reduction Model (WARM). In the U.S., landfill regulations require all landfills to be covered or “capped”, so we apply the lower avoided methane factor of 0.55 tonnes CO₂e per tonne of untreated food waste.

9.7 DETERMINE THE SUBSTITUTION RATIO

We assume natural gas replaces diverted FW-biogas in boiler fuels and CHP systems. As with manure, we determine the substitution ratio for CHP applications based solely on the biogas production rate per kg of feedstock. FW has a higher methane production rate per kg than manure due to its high concentration of organic material. For electricity applications, we use the substitution ratio based on the kilowatt-hours (kWh) of electricity produced per volume of biogas from the EPA AgStar database. Combining this value with the estimated volume of biogas produced per kg of feedstock from GREET, we calculate a substitution factor of 0.6 kWh per kg of food waste diverted.

For FW that is directly incinerated, we determine the substitution ratio based on the energy content of FW and a power generation efficiency factor for municipal solid waste (MSW) reported in GREET. Approximately 1.53 kWh of electricity is produced per kg of FW incinerated.

9.8 DETERMINE THE YIELD FACTOR FOR BIOFUEL CONVERSION

We follow steps similar to those in the manure case study to determine the yield of biogas produced from a tonne of food waste. We calculate biogas production data using the median digester VSR from GREET and a kg VS/kgTS ratio from the literature (Kleinheinz, 2013). Food waste has a higher kg VS/kg TS ratio than manure, indicating that its organic content is more efficiently converted to methane. The final yield factor for FW-derived biogas is 0.22 kg fuel per kg feedstock.

9.9 PERFORM DISPLACEMENT EMISSIONS CALCULATION

Our final estimate for indirect displacement emissions for is -49 g CO₂e/MJ for FW-derived biogas. The low level of displacement emissions for this pathway is due largely to avoided methane release from landfills.

10. CASE STUDY 10: LANDFILL GAS

10.1 DEFINE THE MATERIAL

Landfill gas (LFG) is produced from the decomposition of organic matter in landfills. Its methane content generally ranges between 45 and 60 percent with the remainder comprised of carbon dioxide and trace amounts of other nonmethane organic compounds (Agency for Toxic Substances and Disease Registry, n.d.). Factors that influence the rate of LFG production include waste composition, oxygen and moisture content, temperature, and the age of waste material.

10.2 ESTIMATE TOTAL SUPPLY AND SHARE OF USES IN EXISTING MARKETS

The U.S. produces approximately 323 billion cubic feet of landfill gas annually (US EPA, 2016a).¹ Landfill gas is primarily captured and used for energy and heat onsite, with a small share flared and leaked at uncapped landfills. High rates of landfill gas capture in the U.S. are driven by federal New Source Performance Standards (NSPS). These standards set limits to the amount of methane released at landfills, requiring many landfills to be equipped with collection systems (U.S. Environmental Protection Agency, 2021).

We consult data on the share of LFG management systems from the EPA Waste Reduction Model (WARM), a tool for quantifying GHG emissions from waste management practices in the U.S. (U.S. EPA Office of Resource Conservation and Recovery, 2020). Recent WARM documentation reports that roughly 92% of landfill methane production is generated at facilities equipped with LFG collection systems; the majority of these landfills also convert captured gas to heat and electricity. The remaining 8% of methane is released at landfills not equipped with collection systems.

To determine the share of LFG converted to heat and electricity, we source information from a database published by EPA's Landfill Methane Outreach Program (LMOP). This database also reports the quantity of LFG upgraded to renewable natural gas (RNG) for use in the transportation market; however, we exclude these volumes from our displacement analysis. Using LMOP data, we find that roughly 84% of LFG is directly converted to electricity while the remaining 16% is used in cogeneration or direct heating applications.

10.3 DEFINE THE AMOUNT OF BIOFUEL

We set demand for LFG-derived biogas equal to half of supply, or 95.4 PJ (94 billion ft³).

10.4 IDENTIFY SUBSTITUTE MATERIALS AND DETERMINE THE REPLACEMENT SHARE FOR EACH END USE

As with the two previous feedstocks, we assume that natural gas replaces LFG in heating applications while grid electricity is substituted with LFG volumes burned directly for electricity. LFG that is flared or vented requires no substitutes, but it does benefit from a negative displacement effect from avoided methane release.

¹ Landfill gas is roughly 58% the energy content of biomethane due to its high CO₂ content

10.5 DETERMINE THE ORDER OF DISPATCH

LFG undergoes three stages of treatment before it is converted to RNG. First, it is filtered to remove moisture and particulates to meet air quality standards. The resulting gas can then be flared or burned directly in boilers. During secondary treatment, additional moisture is removed as well as siloxanes and sulfur. This gas, often referred to as biogas, can be compressed and used for CHP or electricity generation. Advanced or tertiary treatment removes carbon dioxide and additional impurities to upgrade biogas to pipeline quality (U.S. EPA, 2020). This end product, delivered to the fuel sector, is also known as renewable natural gas.

The cost of each treatment varies. Using data from EPA's LFG Energy Cost Model (US EPA, 2016b) for large scale collection facilities, we find that collection infrastructure accounts for approximately 15 percent of total capital expenditures (CAPEX) and 40 percent of operating costs (OPEX) (Table 6). With the exception of pipeline interconnection fees, gas conditioning and compression account for the remainder of the costs. Thus, facilities already equipped with secondary treatment will incur the least cost to upgrade LFG to RNG while facilities with no treatment systems in place will incur the highest costs.

Table 6. LFG upgrading costs (adapted from EPA LFG Energy Cost Model)

LFG upgrading costs	Flow rate (scfm)	CAPEX (2021 USD)	OPEX (2021 USD)
Gas collection	600	\$1,300,000	\$218,000
Gas conditioning & compression	600	\$7,180,000	\$316,000

Assuming that the end use with the lowest-cost replacement substitute will be dispatched first, we assume that LFG is first diverted from CHP and combustion applications, next from flares, and finally diverted from uncapped landfills. Because the supply of LFG used in heat and power production today already exceeds the 95.4 PJ biofuel demand threshold, we assume LFG is only diverted from these applications at a rate equivalent to its current share of consumption.

10.6 IDENTIFY LIFE-CYCLE EMISSIONS FOR EACH SUBSTITUTE MATERIAL

We source upstream and combustion emissions for natural gas from GREET and average U.S. grid-electricity CI factors from EPA's eGRID database.

We draw data on the quantity of methane released from uncovered and covered landfills from the EPA Waste Reduction Model (WARM) and data on emissions from LFG flares from GREET documentation (Mintz et al., 2010). Due to the large volume of recovered LFG used for electricity and heat generation, both of these factors are omitted in our final displacement emissions calculations.

10.7 DETERMINE THE SUBSTITUTION RATIO

We reference LFG-to-electricity conversion estimates from the EPA LMOP database. For this case study, our starting feedstock is measured in volumetric rather than weight units, so we calculate the substitution ratio in kWh electricity produced per cubic meters of LFG diverted. For natural gas substituted in CHP or boiler applications, we calculate the substitution ratio based on the LHV of both fuels. LFG has a substantially

lower LHV content than natural gas; we calculate its substitution ratio at approximately 0.57 m³ of gas per m³ of feedstock displaced.

10.8 DETERMINE THE YIELD FACTOR FOR BIOFUEL CONVERSION

LFG to RNG upgrading involves increasing the methane content of fuel and removing existing impurities. We use data from GREET to estimate the conversion efficiency between both gaseous compounds. Approximately 85% of LFG is converted to RNG during upgrading on an energy basis with an additional 2% lost due to leakage. In total, we calculate a final yield factor of 0.837 for this pathway.

10.9 PERFORM DISPLACEMENT EMISSIONS CALCULATION

Our final estimate for indirect displacement emissions is 51 g CO₂e/MJ for LFG-derived biogas.

CONCLUSION

Displacement analysis is an important tool for quantifying indirect emissions associated with biofuels production. Increased demand for biofuels can have both disruptive market effects and adverse environmental consequences, in addition to the emissions associated with feedstock to fuel conversion. Of the 10 feedstocks studied in this exercise, we find that one (sawmill residue diesel) exceeds the CI score of conventional fossil fuels when taking into account their full range of emissions effects. Additionally, other feedstocks considered very low-carbon, such as landfill biogas and tallow biodiesel, may only provide moderate emissions reduction when displacement emissions are considered. Broadening the scope of life-cycle analyses to include indirect emissions can help guide policymakers to tighten feedstock eligibility criteria within a low-carbon fuels program. Improved sustainability measures will ensure that these programs prioritize feedstocks with the greatest emissions reductions and exclude those that may have hidden adverse environmental impact.

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