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Alternative uses and substitutes for wastes, residues, and byproducts used in fuel production in the United States

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Introduction

Policymakers aiming to reduce the greenhouse gas emissions from transportation fuels have expressed interest in supporting fuels derived from wastes and residues to avoid the significant indirect land use change (ILUC) emissions associated with food-based biofuels. Regulators and life-cycle analysts typically do not allocate greenhouse gas (GHG) emissions from the use of wastes, residues, and byproducts in biofuel production because increased demand for these materials is not generally expected to lead to significantly increased production. For example, we would not expect increased demand for tallow to lead to increased cattle production, since tallow represents such a small fraction of the total value of a cow (Rosenfeld & Abella, 2015). This is in contrast to other biofuel feedstocks, such as corn, where its use in biofuel is expected to result in increased corn production and acreage globally.

At the same time, it is important to consider whether the use of byproducts in fuels is likely to have an impact on alternative uses of those materials. Changes in prices of the waste or residue could drive the industry currently using the material to seek substitutes. Potential replacements for these materials have different climate impacts, which change the net GHG effect of using wastes and residues for fuel production. Particularly, the production of substitute materials could have high life-cycle emissions. In other words, while the use of wastes and residues in biofuel production is unlikely to significantly increase the production of those materials, there still could be significant indirect GHG emissions from displacement effects.

Previous research has explored displacement effects of using wastes and residues in biofuel production in California and Europe. In 2009, the U.K. Renewable Fuels Agency and the Department for Energy and Climate Change commissioned Ecometrica to develop a methodology for quantifying the indirect GHG emissions from using wastes,

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residues, and byproducts for biofuels or bioenergy, providing case studies for four materials: molasses, municipal solid waste, straw and tallow (Brander et al., 2009). A 2017 ICCT study assessed the indirect emissions of advanced fuel pathways that would qualify under the recast of the Renewable Energy Directive (RED II) (Searle, Pavlenko, El Takriti, & Bitnere, 2017). Malins (2017) also provided a methodology and assessment of displacement emissions from several feedstocks that would qualify as a waste or residue under RED II. ICF International (2015) published policy recommendations for rules on categorizing biofuel feedstocks as either primary products, byproducts, residuals, or wastes (Rosenfeld & Abella, 2015).

Recognition of the displacement impacts of using wastes for biofuel has appeared already in policy contexts. For example, the U.S. Environmental Protection Agency (EPA) recently accounted for the GHG impacts of displacing distillers sorghum oil used in biodiesel from livestock feed (Renewable Fuel Standard Program: Grain Sorghum Oil Pathway, 2018). The European Parliament's Environment, Public Health, and Food rapporteur proposed accounting for indirect emissions in the RED II, based on estimates in Searle, Pavlenko, El Takriti, and Bitnere (2017) (Eickhout, 2017).

Since most previous work on displacement effects has focused on the EU context, this paper aims to support displacement analyses in the United States in regulatory and research contexts by providing relevant data on byproducts, wastes, and residues that are currently used or might be used for biofuel production. We use publicly available information on current U.S. supply, trends and changes in supply, amounts currently used in biofuel, and exports and imports.

We include agricultural residues and forestry residues in this study, but it is important to consider these residues' important ecological role in supporting biodiversity, reducing erosion, and supporting soil health. We also provide information, when applicable, on other current uses of these materials, providing numerical estimates, when possible. We focus primarily on the use of these materials in the United States but sometimes consider the use of the material globally, depending on the market and the region where it is most commonly produced. We address substitutes for these other current uses to begin to identify potential displacement effects. A sister study discusses methodologies to estimate displacement emissions of wastes, residues, and byproducts used in biofuel (Pavlenko & Searle, 2020).

Oil and fat byproducts

Byproducts made of fats, oils, and greases (FOGs) can be used to produce biofuel via several technologies. The most common commercial-level conversion technologies are transesterification to produce biodiesel and hydroprocessing to produce renewable diesel (Baldino, Berg, Searle, & Pavlenko, 2019). Table 1 shows the current supply, expected production trends, use in transport fuel, and trading information for several common FOG byproducts. Zhou, Baldino, and Searle (2020) provide more-detailed information about the projected production of fats, oils, and greases, as well as their alternate uses, and include an analysis on the projected availability of these feedstocks for use in biomass-based biodiesel (BBD) in the United States. In general, in the tables in this study, if there is no clear trend for the production of a byproduct, five-year averages are presented as the current supply. When an increasing or decreasing trend occurs, the value for the current supply reflects the most recent year for which data is available. For most byproducts, current use in transport fuel comes from the U.S. Energy

Information Administration (EIA). Zhou, Baldino, and Searle (2020) present more data on production, use in biodiesel, and imports and exports of FOGs.

Table 1. Current supply, production trends, use in transport fuel, imports and exports, and major data sources for fats and oils. All values are in thousands of metric tons. Current use for transport fuel comes from the U.S. Energy Information Administration (2020).

Byproduct	Current supply	Production trends	Current use in transport fuel	Imports	Exports	Major data sources
Yellow grease	910	Increasing	630	23	290	National Renderers Association (2019); U.S. Census (2011); USDA NASS (2019a)
Inedible tallow	1,600	Increasing	181	51	280	National Renderers Association (2019); Centrec (2014); USDA NASS (2018)
Inedible poultry fat	750	Increasing	100	0	19	National Renderers Association (2019); Brorsen (2015); Centrec (2014)
Inedible pork fat (white grease)	620	Increasing	270	24	0.4	National Renderers Association (2019); Centrec (2014)
Distillers corn oil	1,700	Peak around 2020, then begin to decrease	720	0	0	USDA ERS (2019a); USDA ERS (2019b)

In this study, we assume that yellow grease is primarily composed of used cooking oil (UCO). Traditionally, yellow grease is a fat blend traded on specification, not raw material composition (Swisher, K., personal communication, December 17, 2018). The National Rendering Association assumes that used cooking oil and yellow grease are similar enough that they can be categorized together (Swisher, K., personal communication, December 17, 2018). When considering yellow grease as a feedstock for biodiesel production, the collected amount is more relevant than total production because UCO is not collected from every source. In particular, collection of UCO from private homes is generally challenging (Hillairt, Allemandou, & Golab, 2016).

Informa Economics (2011) reports that approximately half of restaurants in the United States collect UCO. This number has increased and is likely to continue rising, so it is possible that more UCO could be collected in the future. Other potential sources of UCO could include large institutions, such as universities and prisons.

Figure 1, which combines data from the U.S. Census (2011), the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) (2019), and the National Renderers Association (2019), illustrates estimates of yellow grease supply and trade over time. Overall data availability on yellow grease is poor. The U.S. Census collected data on yellow grease supply from 2003 to 2010 and not thereafter. The USDA NASS began reporting yellow grease supply in 2015, so there is a data gap from 2011 to 2014. Piecing together data from these two sources, it appears that yellow grease supply has increased, while exports of yellow grease have steadily declined, most likely because of elevated domestic demand for biodiesel and renewable diesel production. There is still demand for imported U.S. UCO in Europe for use in biofuel (National Renderers Association, 2019).

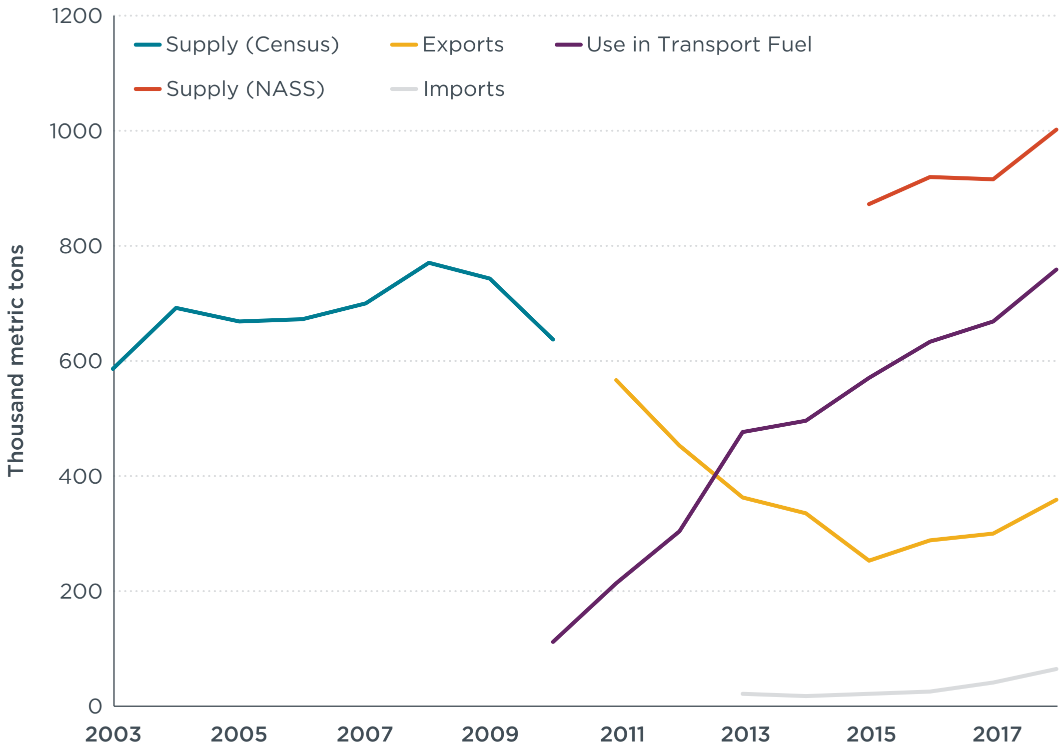

Figure 1. Production of yellow grease in the United States. 2003–2010 data from U.S. Census (2011); 2016–2018 data from USDA NASS (2019). Data of yellow grease supply between 2011 and 2015 is unavailable. Import and export data comes from the National Renderers Association (2019).

Table 1 also includes inedible animal fats—tallow, poultry fat, and inedible pork fat—also known as white grease. We assess only inedible animal fats in this study because these products are commonly used in biofuels, and it may be less likely that edible animal fats, which have higher market value, would be used in biofuel production. As with yellow grease, there has not been continuity in data collection for tallow, white grease, and poultry fat from a single source. The Census reported data from 2002 to 2010, and the National Renderers Association for years thereafter. Figure 2 shows that inedible tallow production declined over the past several years as beef production decreased but rose again in recent years. It also shows that the amount used in biofuel production has remained flat while exports have declined. Exported inedible tallow primarily goes to Mexico (U.S. DOE, 2017). Inedible poultry and white grease are not exported in large volumes; white grease is exported primarily in edible form. More white grease is used in biofuel production than inedible tallow (Table 1). The USDA Economic Research Service (2019a) predicts that production of poultry meat and red meat will increase over the next 10 years, so we estimate that production of inedible tallow, white grease, and inedible poultry fat will increase proportionally. The number of cattle is expected to drop, but the USDA projects that this will coincide with increases in slaughter weights.

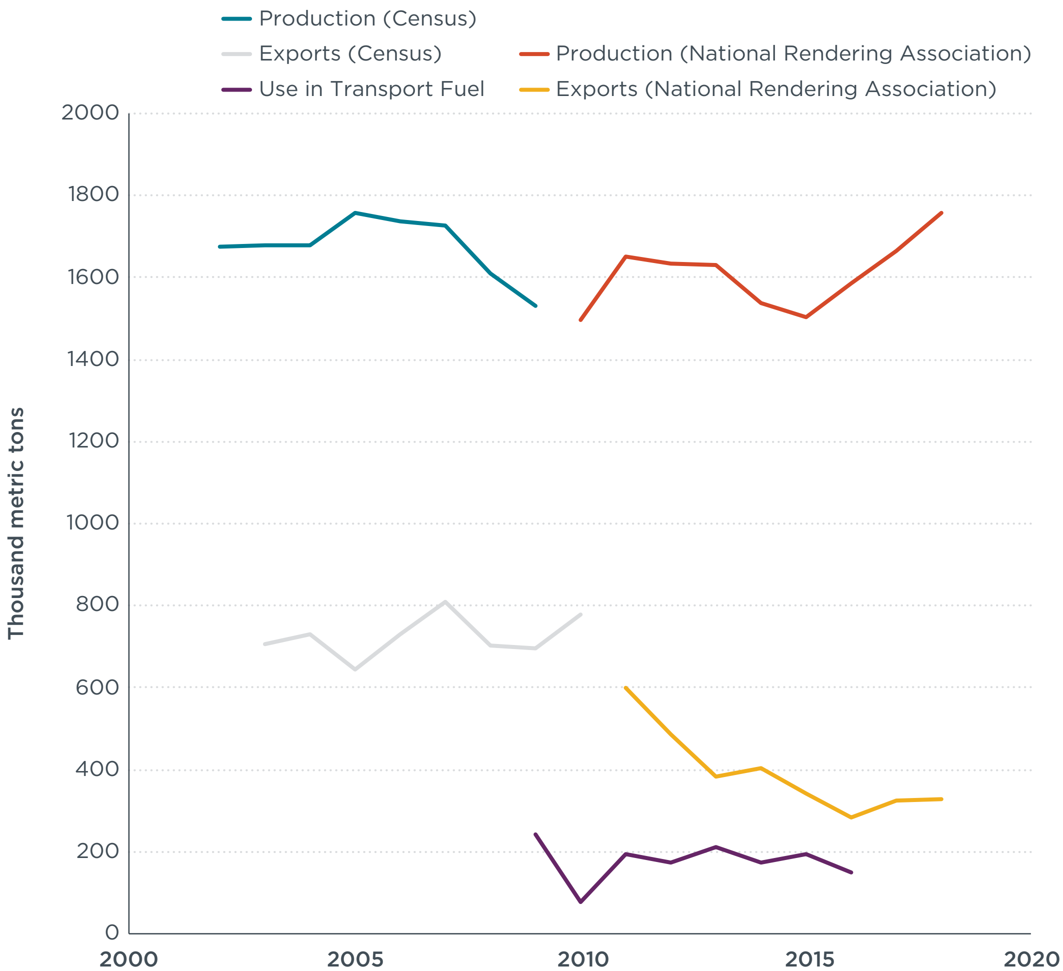

Figure 2. Inedible tallow production, use in transport fuel, and export estimates from the United States since 2002, in thousands of metric tons. Data retrieved from Census, National Rendering Association, and the U.S. Energy Information Administration (2020).

Finally, Table 1 includes distillers corn oil (DCO), which is inedible corn oil from distillers grains with solubles (DGS), a byproduct of corn ethanol production. In the milling process, the starch from the kernel of corn is converted into sugar and then the sugar into ethanol. The nonstarch components that remain are DGS. DGS contains DCO, 60%–70% of which can be pressed out. This corresponds to 6 to 7 liters of corn oil per 100 liters of corn ethanol, according to a California Low Carbon Fuel Standard pathway application (California Air Resources Board, 2010). The value for current supply in Table 1 shows the amount of DCO that is pressed out of DGS and does not include DCO remaining in DGS. The USDA projects corn inputs to ethanol plants to peak in 2020 and decrease afterwards, and we expect the supply of DCO to follow the same trend. However, as noted in Zhou, Baldino, and Searle (2020), this outcome could change with changes in policy—for example, relaxation of the Reid vapor pressure requirement for E15 in the summer months and the federal rollback of fuel economy standards, both of which could potentially increase ethanol demand.

Table 2 shows current uses as well as potential substitutes for all of the waste FOGs discussed above. Each of the FOGs assessed here is currently used in livestock feed. In 2008, the Food and Drug Administration implemented rules limiting the use of cattle products in food and feed because of concerns about bovine spongiform encephalitis, or mad cow disease (U.S. Food and Drug Administration, 2018). According to U.S. Census data, the amount of inedible tallow used in animal feed decreased sharply from 2008 to 2010 (the last year for which we have data, which we present in Table 2). As of 2011, almost half of the inedible tallow in livestock feed went to feeding cattle, 30% to swine, and 21% to poultry. As for white grease, 68% of what's used in livestock feed is for swine, followed by poultry at 28% and cattle, 3%. Almost 90% of poultry fat used in livestock feed is for poultry, followed by swine at 6%. About 65% of yellow grease used in livestock feed is for poultry, and the rest is almost evenly split between cattle and swine (Informa Economics, 2011).

Table 2. Current uses of fats, oil, and grease byproducts in the United States, potential substitutes for current uses, and data sources for this information. All values are in thousands of metric tons.

Byproduct	Livestock feed		Pet food		Oleochemicals		Major Data Sources
	Current use	Substitutes for current uses	Current use	Substitutes for current uses	Current use	Substitutes for current uses	
Yellow grease	50	Corn			1	Palm-derived products	Informa Economics (2011)
Inedible tallow	160	Corn	160	none	500	Palm-derived products	U.S. Census (2011); Centrec (2014); de Guzman (2013); Informa Economics (2011); Brander et al. (2009)
Inedible poultry fat	690	Corn	260	none			Centrec (2014); Brander et al. (2009); Informa Economics (2011)
White grease	110	Corn	160		30	Palm-derived products	Centrec (2014); Informa Economics (2011)
Distillers corn oil	860	Corn					U.S. Grains Council (2018)

The only major use of DCO is in livestock feed. DCO that has been removed from DGS is added to pig and chicken feed because these animals cannot process the fiber in DGS, while cattle are fed DGS with or without the DCO extracted. Poultry and swine are fed around 51% of the DCO supply (Table 2). Figure 3 illustrates the DCO supply, the amount going to fuel production, and what is fed to poultry and swine. Five percent of DCO goes to industrial resources, which is not shown in the figure (U.S. Grains Council, 2018). In general, this figure shows that an increase in the amount of inedible corn oil pressed out of DGS for use in transport fuel has led to a corresponding decrease in the amount remaining in DGS that is then fed to poultry and swine.

As of 2013, around 70% of ethanol plants extracted DCO (Jessen, 2013). Assuming that the 30% of ethanol plants that do not extract DCO produce around 30% of DGS, we estimate that approximately 880,000 metric tons of DCO remain in DGS. It is likely that this DGS is currently fed to cattle. Were there to be a policy incentivizing the use of DCO in biofuel, this additional DCO could be extracted, diverting this source of oil for cattle. It is uncertain whether the DCO that is currently extracted and fed to poultry and swine, or the DCO that remains in the DGS and is fed to cattle, would be diverted from its current use first. A recent ICCT analysis of historical U.S. livestock feed ingredients found that the substitute commodity for DCO in feed is most likely the addition of more corn grain (Searle, 2019). Based on this result, we assume that corn is the substitute in livestock feed for each of the FOGs listed in Table 2.

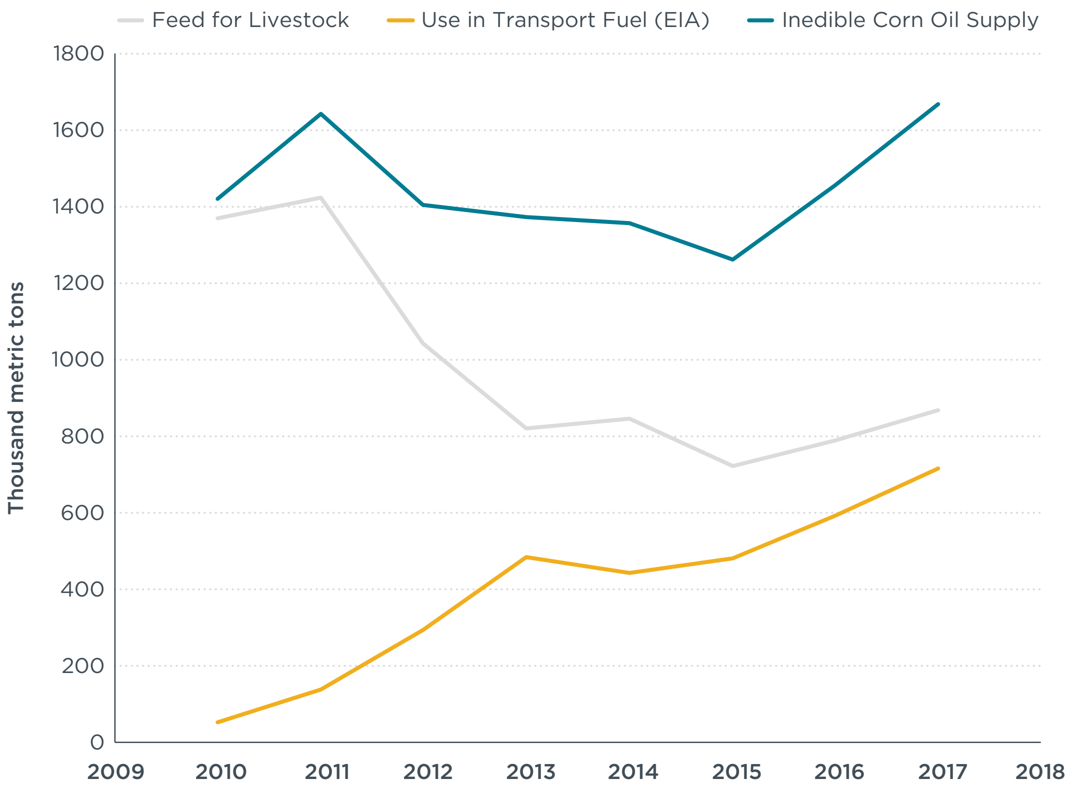

Figure 3. Inedible corn oil (distillers corn oil, DCO) supply, use of DCO in transport fuel, and the amount going to feed for poultry and swine in the United States since 2009, in thousands of metric tons.

We base our estimate of the amount of FOGs in pet food on a 2011 Informa Economics study, which provides estimates of the percentage of each FOG that is used in pet food. There is apparently no substitute for tallow in pet food because its unique meaty flavor is necessary to make pet food palatable for animals (Brander et al., 2009). We assume that this is also the case for white grease and poultry fat in pet food, given that they are also animal fats.

We estimate the use of yellow grease, inedible tallow, and white grease in the oleochemical industry based on 2011 U.S. Census data on use of these FOGs in industrial products such as fatty acids, soaps, and lubricants. More information on how we derived estimates for each FOG's use in industrial products is provided in Zhou, Baldino, and Searle (2019). The palm-derived products that replace FOGs in oleochemicals could include palm stearin, palm oil, and palm kernel oil. The values for the current use of yellow grease in livestock feed and oleochemicals in Table 2, added to net exports and current use in transport fuel, exceeds current supply of this material. This discrepancy could be due to our use of different data sources to estimate the amount of yellow grease falling into these categories.

In addition to the current uses addressed in this table, Informa Economics (2011) estimates that approximately 8% of yellow grease is stolen per year due to the high value of this feedstock; specifically, the oil rendering industry loses between $45 million and $75 million per year (Associated Press, 2019).

Crop-based byproducts

Current supply, production trends, trade, and use of crop-based byproducts besides inedible corn oil are presented in Table 3. Palm Fatty Acid Distillates (PFADs) are a part of oil palm fruit that are removed during the refining process to make palm oil edible. Typically, the crude palm oil refining process consists of 5% PFADs and 95% palm oil (Handojo et al., 2018). We consider the supply and alternative uses of PFADs globally as there is no production in the United States. The majority of PFAD production occurs in Indonesia and Malaysia. Given that palm oil production is rising, we expect PFAD output to increase. The United States imports PFADs, but there is no publicly available information that PFADs are used in U.S. biodiesel (Kodjak, 2013).

Table 3. Current supply, production trends, use in transport fuel, imports and exports, and major data sources for crop-based byproducts, excluding inedible corn oil, in the United States. All values are in dry, thousands of metric tons.

Byproduct	Current Supply (thousand metric tons)	Production Trends	Current Use in Transport Fuel	Imports	Exports	Major data sources
Palm fatty acid distillate (PFAD)[a]	2,500	Increasing	0 (in the U.S.)	—	—	Neste (n.d.)
Palm oil sludge[a]	1,000 (potentially)	Increasing	Probably 0	—	—	USDA FAS (n.d.)
Sugar cane bagasse[b]	103,000	Increasing	40	—	—	Barros (2016); Birru (2016); Dias et al. (2015); FAO (2019)
Molasses	2,200 (Molasses C)	Remain the same	None	39000 (Molasses C)	175000 (Molasses A, B and C)	FAO (2019); OECD iLibrary (2018)
Corn stover	30,800	Unclear	160	0	0	FAO (2019)
Wheat straw	57,000	Unclear				FAO (2019); Scarlat (2010)
Wheat starch	120	Unclear	X	0	0	FAO (2019); U.S. International Trade Commission (1998); White Energy (2018)

Note: Dashes mean the data is not publicly available. X means that the byproduct is put to this use, but the amount is not publicly available.
[a] We consider use of these byproducts on a global level, not just within the United States.
[b] We consider sugar cane bagasse in Brazil only.

Table 4 shows alternative uses of PFADs. If there is an increase in demand for PFADs in the United States for use in biodiesel, the United States would most likely expand imports, which would divert PFADs from other uses on a global scale. A representative from Endicott Biofuels, a biodiesel company based in Texas, stated that were the company to produce biodiesel from PFADs, it would import the material from Southeast Asia rather than using PFADs already on the U.S. market (Endicott Biofuels, 2013).

Table 4. Current uses of crop-based byproducts, potential substitutes for current uses, and data sources for this information, in the United States. All values are in dry, thousands of metric tons.

Byproduct	Energy type		Fertilizer		Livestock Feed and/or Bedding		Major data sources
	Currently used?	Substitutes for current uses	Currently used?	Substitutes for current uses	Currently used?	Substitutes for current uses	
Palm fatty acid distillate (PFAD)[a]	Possibly	Fuel oil			X (feed only)	None	Malins (2017); Onetti & Grummer (2004)
Palm oil sludge[a]	X (biogas from POME)	Possibly liquefied petroleum gas, other palm residues	X	Synthetic fertilizer			Ji, Eong, Ti, Seng, & Ling (2013); Subramaniam & Sulaiman (2008)
Sugar cane bagasse[b]	X	Most likely natural gas and grid electricity. Possibly oil, coal and lignite	X	Synthetic fertilizer			Dias et al. (2015); Mutran et al. (2016)
Molasses C					1,700 (feed only)	Clays, starches, e.g., wheat, whey protein concentrate, and other lignin and hemi-cellulose products	Mavromichalis (2016); Oregon Tilth (n.d.)
Corn stover			X	Synthetic fertilizer	Approximately 15,000	For bedding: rubber mattresses, sand, gypsum, dried manure, switchgrass. For feed: corn	Glassner, Hettenhaus, & Schechinger (1999); Kadam & McMillan (2003); Samson, Delaquis, Deen, Debruyn, & Eggimann (2016)
Wheat straw			X	Synthetic fertilizer	X	For bedding: rubber mattresses, sand, gypsum, dried manure, switchgrass. For feed: corn	Klasing (2012); Center for Agriculture, Food and the Environment (2019)
Wheat starch					Possibly	Corn	Johanson (2017)

Note: X means this is a current use of the byproduct, but the amount is not publicly available.
[a] We consider use of these byproducts on a global level, not just within the United States.
[b] We consider sugar cane bagasse in Brazil only.

The most important use of PFADs is as an additive to livestock feed, particularly for cattle, which is most likely the main use of PFADs imported to the United States. We were unable to find publicly available data on the amount of PFADs currently used in livestock feed in the United States. PFADs are combined with calcium to produce calcium soaps, which are rumen-protected fats, a staple supplement for the dairy industry (Onetti & Grummer, 2004). Rumen-protected fat raises the energy density of the overall ration of feed because it has a higher metabolizable energy density than other feed ingredients like distillers grains or other dry feed. Specifically, it does not inhibit the ability of the rumen to break down fiber as other vegetable oils do (Hibma, 2010). Substitutes for rumen-protected fats can be produced by adding calcium to fatty acids or by hydrogenating or fractionating vegetable oils (Malins, 2017). Specifically, either palm oil or soybean oil could be hydrogenated; the choice might depend on the C16 (palmitic acid) content (Eastridge, 2002).

Due to the unique nutritional value of PFADs, U.S. livestock farmers' demand for them is likely to be more inelastic than it is for the other fats and oils that they put into livestock feed. We thus think it is unlikely that the use of PFADs in biofuel production would displace this material from livestock feed.

It is also possible that PFADs are burned for energy in boilers in palm oil refineries. The substitute for this use is likely to be fuel oil as the cheapest alternative (Table 4). In addition to the alternative uses listed in Table 4, other applications of PFADs on the global market are oleochemicals and niche uses such as the production of vitamin E. For oleochemicals, we assume that the substitute for PFADs would be palm oil-derived products, similarly to the FOGs assessed above. We assume niche applications would not be replaced at all, reflecting the probably limited amount of PFADs going to this use and lack of information.

Palm oil sludge is a residue of palm oil production that could potentially be used for biodiesel or renewable diesel production. Like PFADs, we assess the global market of this material. Palm oil mills produce wastewater from the milling process, called palm oil mill effluent (POME). POME must go through a treatment pond before mills are allowed to discard it. There, organic matter in the wastewater biodegrades before it is discarded into a waterway. Palm oil sludge is the oily matter that floats to the top of these treatment ponds, which can potentially be collected for further use. POME can have varying characteristics due, for example, to different extraction techniques and quality of the palm fruits, which can then affect the quality of the palm oil sludge. We find two recent studies with information on the potential supply of palm oil sludge, which we use for our estimate (Table 3). Liew, Kassim, Muda, Loh, and Affam (2015) provide information on the amount of oils and greases in wastewater from the palm milling process. This aligns with Manurung, Ramadhani, and Maisarah (2017), who find that palm oil sludge supply is equal to 2% of palm oil production. The potential supply we report in Table 3 also incorporates an extraction rate of 64.3% for wastewater streams that use a dissolved air flotation system to remove oil (Show, 2008). Like PFAD supply, we expect the supply of palm oil sludge to rise with increases in palm oil production.

Palm oil sludge is currently used for energy and fertilizer, and there is little evidence that harvesting it for use in biofuel would displace current uses (Table 4). Were palm oil sludge to be left in the POME, the biogas produced from the treatment pond could be captured and combusted for energy. However, as of 2012, the most recent year for which information was available, only 5% of palm oil mills in Indonesia collect biogas from POME treatment ponds. In Malaysia, as of 2011, the most recent year for which data is available, only 12.9% of palm oil mills completed biogas plants, while 3.8% had plants under construction and 35.2% had plans to build them (Climate, Energy, and Tenure Division, 2014; Ji, Eong, Ti, Seng, & Ling, 2013).

Little information was publicly available on the current uses of palm oil sludge. In the case that palm oil mills have gas units to generate power from biogas, liquefied petroleum gas could possibly be the substitute for the biogas (Ji et al., 2013). Some palm oil mills that employ POME for energy may have solid-fuel boilers in addition to gas boilers and could thus potentially replace POME biogas energy with increased use of solid fuels. Substitutes for solid-fuel boilers could be other palm residues, such as empty fruit bunches (Paltseva, Searle, & Malins, 2016). The findings in Paltseva et al. (2016)

suggest that more than enough palm biomass residues exist to replace the amount of POME biogas currently used in boilers, in excess of the amount of palm biomass used in material uses. For example, palm kernel shells are used as a material for road surfacing on plantation and mill estates, although the amount of shells going toward this use is unclear (Ji et al., 2013; Yusoff, 2006). Additionally, some palm oil sludge could be or is currently used as a fertilizer, in which case the most likely replacement would be conventional fertilizer (Subramaniam & Sulaiman, 2008) (Table 4). However, it is not clear whether fertilizer represents a significant current use of palm oil sludge.

Sugar cane bagasse is fiber that remains in sugar cane stalks after the sugar juice has been pressed out. We consider the supply only in Brazil because Brazil is the world's largest supplier of sugar cane ethanol, producing 34 billion liters in 2019, and we expect bagasse ethanol to be feasible only where sugar cane ethanol facilities already exist (Barros, 2019) (Table 3). This is because companies with first-generation facilities can create additions, which are more cost-effective to build than stand-alone cellulosic biofuel facilities.

We estimate sugar cane bagasse production as follows. We subtract the percentage of sugars in clean sugar cane stalks, 15.4%, from the percentage of dry matter in clean stalks, 29%, to estimate the percentage of lignocellulosic material—bagasse—in clean, dry stalks at 13.6% (Birru, 2016). We multiply this by the average sugar cane production in Brazil from 2013 to 2017 to estimate Brazil's supply of sugar cane bagasse (FAO, 2019). The sugar cane bagasse supply is expected to increase from a current level of 103 million dry metric tons to somewhere between 116 million and 160 million dry metric tons in 2024 (Marin, Martha, Cassman, & Grassini, 2016).

Sugar cane bagasse is used for energy in sugar cane production plants as well as in fertilizer, although we are not sure how much is put to these uses (Table 4). We find that almost all sugar cane plants in Brazil are energy self-sufficient, with some selling surplus electricity to the grid (Ensinas, Nebra, Lozano, & Serra, 2007). Natural gas is the most likely energy source that would replace sugar cane bagasse because most of the plants have steam turbines (Dias et al., 2015). However, depending on the specific energy system at a plant, oil, coal, and lignite are also possible substitutes. For excess bagasse-derived electricity that is sold to the grid, the replacement would be increased grid electricity from marginal sources in Brazil.

A previous ICCT study investigated the displacement effects of using molasses in fuel in Europe, where sugar comes primarily from sugar beets. In the United States, sugar comes mostly from sugar cane. There are three stages of crystalizing sucrose, producing three kinds of molasses: A, B, and C. Molasses A is the run-off syrup from the first distillation of sugar production from sugar beets and retains a substantial amount of sugar. Molasses A is typically distilled again, producing Molasses B as the run-off syrup, with a lower sugar content. Molasses C, also known as blackstrap molasses or final molasses, is the most likely biofuel feedstock of the three types because it is the cheapest and cannot be used for additional sugar production (El Takriti, Searle, & Pavlenko, 2017). We report the supply of Molasses C in Table 3. We find 2014 production values from FAO (2019) for Molasses C and predict in Table 3 that molasses production will remain the same or decrease, based on OECD-FAO data, which includes all molasses types (OECD iLibrary, 2018). Though it is likely that only Molasses C would be used in fuel, it is possible that with an increase in incentives for molasses, it could be cost-viable to stop the distillation process after the earlier distillation stages and produce fuel from Molasses A or B.

Molasses C is most commonly used as a substrate for baker's yeast production. Glucose syrup, which is primarily made of corn but can also come from other starchy crops such as potatoes and wheat, can substitute for molasses in the production of baker's yeast (Bekatorou, Psarianos, & Koutinas, 2006). We find that 60% of molasses sugars could be replaced by glucose syrup without any significant influence on yeast biomass growth, and the rest could be replaced with corn steep, a byproduct of corn wet-milling that consists mainly of soluble proteins (Tereos, 2013). If 100% of the molasses sugar were replaced with glucose syrup, there would be reduced yeast growth (Spigno, 2009).

The most recent publicly available estimate of the supply of yeast, from 1989, is 223,500 metric tons (U.S. EPA, n.d.-c). To estimate the amount of molasses needed to produce that amount of yeast, we assume that 50% of the caloric needs of yeast production were met with molasses using a ratio of molasses to yeast that we found in Sokchea et al. (2018). We subtract this amount of molasses, 517,000 dry metric tons, from the total supply of 2.2 million metric tons (Table 3), and assume the remaining 1.7 million metric tons go to livestock feed (Table 4). Molasses is a valuable input in livestock feed because it acts as a binding agent for the feed and provides valuable minerals, as reviewed in El Takriti et al. (2017). Unlike PFADs, however, there are some viable substitute feedstocks, including clays, starches such as wheat, whey protein concentrate, and various lignin and hemi-cellulose products such as rice hulls. Molasses is also used in the production of rum, but there is no available information on the quantity used for this purpose (Risen, 2012) (Table 4). The most likely substitute for molasses in rum production would be sugar cane juice.

Corn stover—or stalks, leaves, and cobs—and wheat straw are other agricultural residues that could be used in the production of fuel. To estimate the amount of corn stover and wheat straw available for fuel production in the United States, we find corn and wheat production from FAO (2019). To calculate the amount of corn stover, we use a 1:1 ratio for corn stover and corn grain (Oak Ridge National Laboratory, 2011). Using a ratio between wheat yields and residues from Scarlat (2010) and average 2017 U.S. wheat yields from FAO (2019), we calculate a ratio of 1.193 for wheat straw and wheat production. We then subtract an assumed moisture content of 15% from our estimated production values for corn stover and wheat straw to report the supplies in dry weight. In reality, a lower supply of these residues would be available for harvest to use in biofuel because some of the residues would remain in the field as impossible to collect and to maintain ecological function and return nutrients to the soil (Oak Ridge National Laboratory, 2011).

At least 5% of corn stover is used for livestock feed and bedding, and wheat straw is also used in livestock bedding, but it is unclear how much (Table 4). Likely substitutes for livestock bedding are switchgrass as well as other materials including rubber mats, sand, gypsum, and dried manure (Searle et al., 2017). In some regions, corn stover could contribute 20%–30% of dry forage matter for livestock, which are allowed to graze on fields after grain is harvested (Kadam & McMillan, 2003). We estimate that 770 thousand metric tons of wheat straw and corn stover are used for mushroom cultivation, representing 0.1% of the combined total of corn stover and wheat straw available in the United States. We retrieve mushroom production from the USDA Agricultural Marketing Resource Center (2018), while the amount of compost that's required as well as an assumption of 75% agricultural residues in compost, comes from Royse (2014) and Stamets (2000).

In aggregate, other uses of agricultural residues in the United States are relatively small compared with production, and large amounts of biofuel could theoretically be produced from this resource without displacing it from other uses. However, at a local scale it is possible these other uses may be displaced if, for example, a biofuel facility sources agricultural residues from an area where a relatively large amount is used for livestock. It is also possible that on a national scale substantial amounts of biofuel could be produced from agricultural residues while allowing enough of this material to remain in fields to reduce erosion and contribute to soil carbon formation. For example, a number of studies estimate or assume that 55%–82% of agricultural residue production should be left in the field to support soil quality in the United States, while the remainder may be harvested (reviewed in Searle & Malins, 2013). In contrast, some studies assume that any removal of agricultural residue results in a loss of soil carbon (Xu et al., 2019).

Wheat starch slurry, a byproduct of the manufacture of wheat gluten, consists primarily of Starch A and, to a lesser extent, Starch B. Starch B consists of smaller granules that account for 30% of the total mass in mature wheat starch (Sieb, 1994). We expect that wheat starch slurry output will increase as wheat production rises (Table 3). The only publicly available information on the use of wheat starch slurry in ethanol comes from White Energy, which produces 57 million liters of ethanol a year from this feedstock. When applying to have it qualify as a waste under California's Low Carbon Fuel Standard, White Energy said it is "entirely landfilled or land-applied" in response to the California Air Resources Board's assertion that Starch A could be a source of cattle feed (Johanson, 2017). However, we find no evidence that wheat starch is land-applied or landfilled, and other resources indicate that it actually has alternative uses. Starch A can be sold as premium wheat starch, or it can remain in the slurry along with Starch B to produce alcohol products (U.S. International Trade Commission, 1998). When Starch A is sold, it is mostly to the paper industry, where it is used as a wet-end adhesive, in surface coating, and as an adhesive for the manufacture of corrugated board (Knight & Olson, 1984).

Forestry and paper industry byproducts

We define forestry logging residues as the small branches, treetops, and stumps that would typically be left in the forest. The Forest Inventory and Analysis National Program of the USDA Forest Service reports that in 2016 there were 106 million cubic meters of logging residues left in harvested forests (Table 5). This amount has increased slightly over time, but the volume most recently reported in 2016 was only 8% greater than in 1991 (Figure 4). The Forest Service does not track the amount of branches, treetops, and stumps that are collected and removed for use in forest products, so we cannot estimate the current use of these materials. Previous ICCT research has shown that a variety of factors affect the amount of forestry residues that could be "sustainably" harvested depending on, for example, location, species, slope, and weather patterns. Ideally, residue retention requirements to maintain ecological function would be determined on a local level (Searle & Malins, 2016). Figure 4 shows the amount of logging residues left in forests by year since 1991.

Table 5. Current supply, production trends, use in transport fuel, imports and exports, and major data sources for forestry and paper industry byproducts. Units are thousands of dry metric tons unless otherwise noted.

Byproduct	Current supply (thousands of metric tons)	Production trends	Current use in transport fuel	Imports	Exports	Major data sources
Forestry residues, i.e., logging residues	106,000	Increasing slightly	0	0	0	USDA Forest Service (2018)
Sawmill residues	64,000	Decreasing	0	0	0	USDA Forest Service (2018)
Black liquor	58,500 (solids)	Unclear	0	0	0	Aryan & Kraft (2020)
Crude tall oil	1,000	Unclear	0	0	(see Table 6)	Aryan & Kraft (2020); Peters & Stojcheva (2017)
Tall oil pitch	147	Unclear	0	0	(see Table 6)	Cashman, Moran, & Gaglione (2015)

There is little publicly available information regarding current uses of logging residues in the United States. Sometimes, subpar limbs are piled and burned in the field because logging companies would rather not waste space with these residues on logging trucks, which have weight limits (Dwivedi, Bailis, & Khanna, 2013; Belton Copp, December 18, 2018, personal communication). Some of the residues that are removed are burned as boiler fuel or chipped for use in mulch. In total, 36 million dry metric tons of wood are used as fuel in the United States, which most likely includes roundwood as well as logging residues (USDA Forest Service, 2012). In general, there is probably some opportunity to increase removal of logging residues sustainably, but if forestry residues currently have other uses, their employment in transport fuels will cause displacement emissions. Particularly, were they used in the heating and power sector, the most likely near-term replacement would be fossil energy or roundwood.

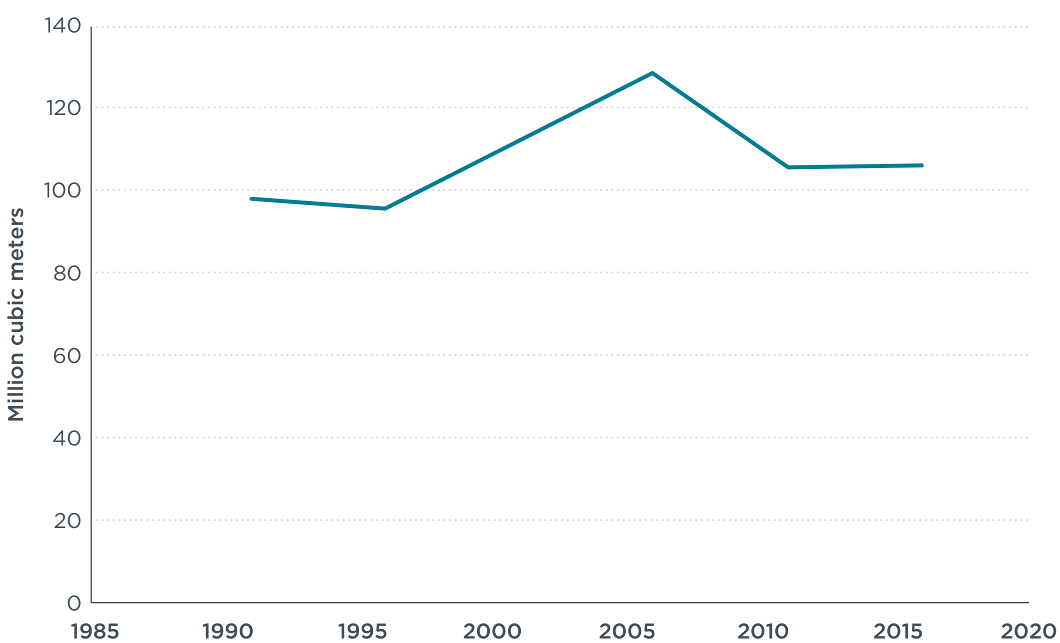

Figure 4. Logging residues remaining in the forest. Data source: USDA Forest Service, 2018.

To estimate the supply of sawmill residue—byproducts of sawing timber—we use 2016 data from the Forest Inventory and Analysis National Program of the USDA Forest Service (2018). Sawmill residues include sawdust and cutter shavings from timber production. This data includes the amounts of sawmill residues employed in fiber products; fuel; other uses including animal bedding, mulch, and decorative bark; and residues that remain unused. The Forest Inventory and Analysis National Program defines fiber products as "derived from wood and bark residues, such as pulp, composition board products, and wood chips for export." We estimate a supply of 60 million metric tons of sawmill residues each year by adding together the amount of sawmill residues in several categories of U.S. Forest Service data: use in fiber products, use in fuel, other uses, and not used (Smith, Miles, Perry, & Pugh, 2007) (Figure 5).

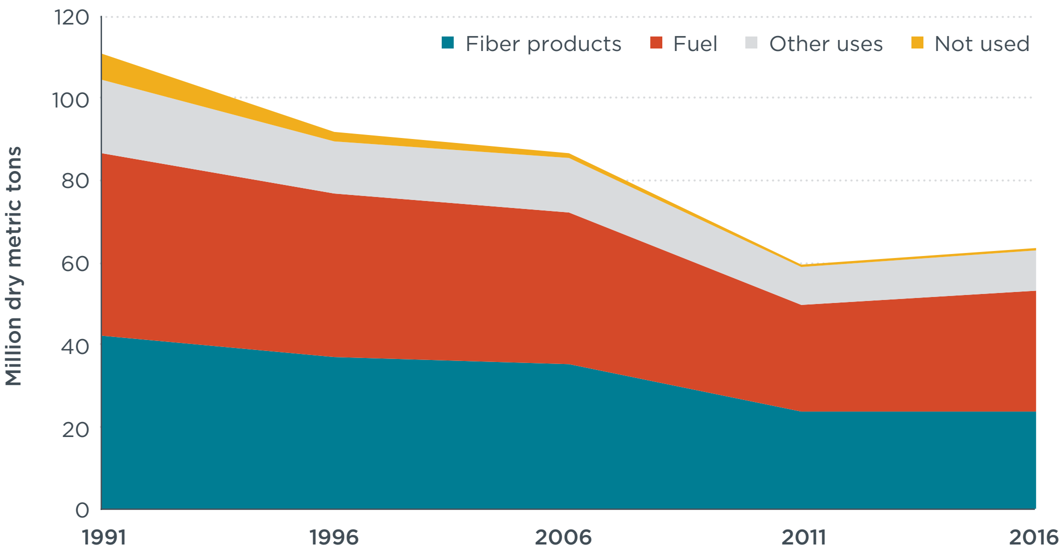

Figure 5. Mill residue disposition in the United States (dry metric tons) since 1991: use in fiber products, fuel, other uses, and unused. Source: USDA Forest Service, 2018.

We see a decrease in supply of sawmill residues since 1991, but it is unknown whether the decline will continue (Figure 5). Considering the quantity of different kinds of mill residues produced since 1991 (bark, coarse, and fine), we do not find major changes in the breakdown of the three types, suggesting that the milling process has not changed much over the past 30 years (USDA Forest Service, 2018). According to the U.S. Forest Service, the decline in mill residue production could be attributed to reduced timber production and increased efficiency and recovery of products during timber processing (Smith et al., 2007). The housing sector is one of the greatest consumers of sawed products in the United States, so it is possible that there is a relationship between the number of housing units that are built in a given year and the sawmill residues produced in that year. However, we do not see a relationship between the amount of sawmill residues and the number of new housing units under construction, making it hard to predict the supply of sawmill residues in the future (Figure 6).

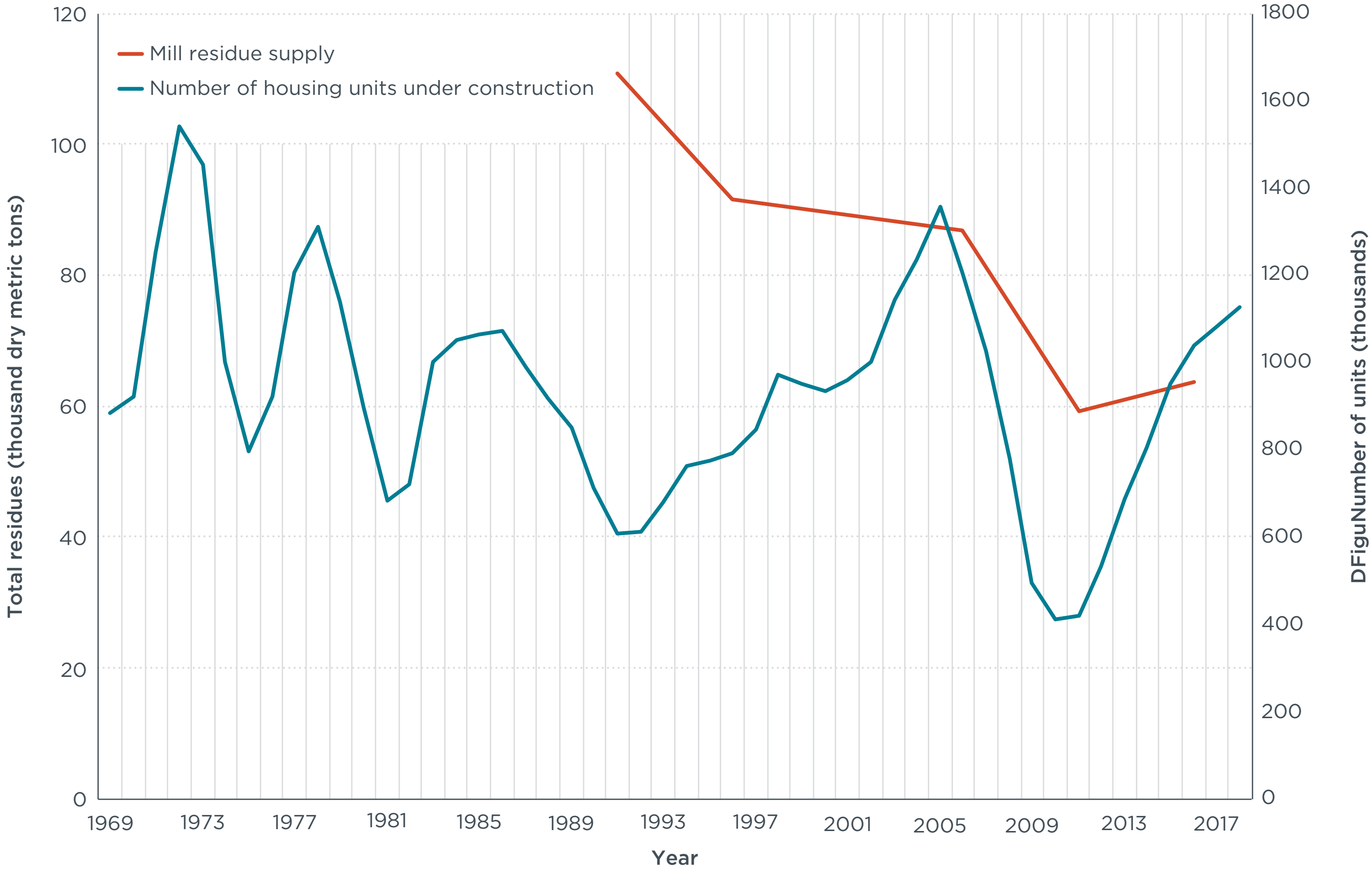

Figure 6. Supply of sawmill residues (dry thousands of metric tons, left axis) and the number of new housing units under construction (thousands, right axis) since 1969 in the United States.

According to the U.S. Forest Service, only 1% of sawdust residues are not currently put to use in the United States (USDA Forest Service, 2018). Since 1991, use of sawmill residues in fuel has increased slightly, from 40% to 46%. At the same time, fewer sawmill residues have gone into fiber products over time, suggesting domestic fuel use displaces use in materials (Figure 5).

Exported wood chips are most likely used as fuel. UN Comtrade (2018) data shows that the United States exported 4 million metric tons of wood chips in 2018. That means exported wood chips represent at most about 20% of fiber production, assuming that the supply of fiber products in 2016 was similar to 2018 and that all wood chips come from mill residues. It is unclear what amount of wood chips are produced from mill residues. There are several boiler types that burn these residues as fuel, including Dutch ovens, fuel cell ovens, suspension-fired boilers, and fluidized bed combustion boilers. The most common is the spreader stoker, which can employ multiple fuels. The most likely replacement if wood residues are diverted to another use besides roundwood is coal (U.S. EPA, 2018c; IEA Clean Coal Centre, 2018).

Pellets are a kind of fiber product that are used for fuel in importing regions such as the European Union. Since the early 2000s, pellets have become the primary solid biofuel commodity. At the same time, trade in wood chips has decreased, partly reflecting sanitary measures that must be taken with wood chips to prevent pests such as beetles and nematodes (Lamers, Junginger, Marchal, Schowenberg, & Cocchi, 2012). K.L. Abt, R.C. Abt, Galik, and Skog (2014) report that the feedstock mix used to produce pellets in the American South shifted from 100% sawmill residues in 2010 to less than 40% sawmill residues by 2014, with the remaining 60% filled by pulpwood. It is possible that the decrease in such use of sawmill residues is related to the overall decline in sawmill residues that occurred since the 1990s. If the availability of sawmill residues continue to decline, pellets may increasingly be made of pulpwood (Figure 6).

It is possible that a small amount of sawdust is used in livestock bedding, which would most likely be classified among "other uses." The Department of Energy (2017) noted that the amount used in livestock bedding varies, since the cost and availability of different types of bedding fluctuates. As previously noted, substitutes for livestock bedding include switchgrass, manure, and nonbiological materials.

Black liquor is a byproduct of pulp production and is used mostly to make paper. When ground wood is washed in chemicals to separate lignin—a complex polymer found in wood—from the cellulose fibers that make up pulp, the lignin remains dissolved in a slurry called black liquor. It is primarily produced in the Southeastern United States, where harvesting is common of loblolly pine, a softwood tree species used for pulp production in that region. Most pulp mills have a black liquor boiler that serves two functions: 1. To boil off the water and lignin to reclaim the chemicals, and 2. To produce heat and steam from the burning of the lignin to power the pulp mill. We collect data on the supply of black liquor from Aryan and Kraft (2020).

We assume that all of the black liquor is used as boiler fuel, except the fraction of crude sulfate salts that is removed to produce crude tall oil, another byproduct used in adhesives and other materials. As natural gas is the cheapest fuel available, we assume it would be the substitute energy source (Kramer, Masanet, Xu, & Worrell, 2009).

Crude tall oil (CTO) comes from processing crude sulfate salts, which are separated from black liquor through a process known as acidulation. In general, 35–40 kg of CTO is produced per metric ton of dry pulp. If all mills recover their full potential of CTO with maximum acidulation, the total estimated potential is 1.2 million to 1.5 million metric tons (Aryan & Kraft, 2020). There are about 100,000 metric tons of CTO in North American storage tanks. This estimate is based on the total number of storage tanks used for exporting CTO and volumes stored in tanks at refineries (Aryan & Kraft, 2020).

Before the production of renewable diesel using CTO in the European Union, 12%–15% of CTO globally was burned to generate energy, according to Peters and Steen (2013), but it is unclear how much is burned now. In North America, CTO is burned only when it is difficult to bring to market, such as from remote regions. An estimated potential of 20,000–30,000 metric tons are being burned in Canadian mills (Aryan & Kraft, 2020). The most likely substitutes for CTOs used for on-site combustion are heavy fuel oil or natural gas (Peters & Stojcheva, 2017).

There is no publicly available evidence that CTO is used in the production of biofuel in the United States, although it is employed in production of renewable diesel at biorefineries in Europe, such as at the UPM Lappeenranta Biorefinery in Finland (UPM Biofuels, 2019). Globally, CTO is distilled primarily for use in the pine chemicals industry, where it is employed in production of tall oil fatty acid, a fuel additive also used for alkyd resins and dimer acids; tall oil rosin, used for adhesives, paper sizing, printing ink, and rubber emulsifiers; tall oil heads, which could be used as fuel oil and process fuel for CTO distillation; and distilled tall oil (DTO), for metal working fluid (Malins, 2017; Cashman et al., 2015). CTO is also used in the oilfield and mining industries, where volumes consumed are estimated to range between 40,000 and 80,000 metric tons a year, depending on demand (Aryan & Kraft, 2020).

Substitutes for rosins include alkenyl succinic anhydride, gum rosin, C5 hydrocarbon resins, and for rosin ester, gum rosin ester, C5 hydrocarbon resins, and acrylic resin. For tall oil fatty acids, substitutes include soybean-food grade vegetable oils, and for DTO, soybean-food grade and C5 hydrocarbon resins (Peters & Stojcheva, 2017). If tall oil pitch and tall oil heads were used for energy, the substitute would be heavy fuel oil #6 (Cashman et al., 2015).

Tall oil pitch is another derivative of CTO production; it is the heaviest material produced during tall oil refining, making it a lower-value material compared with other products of CTO distillation and thus a candidate for biofuel production. We calculate its supply using an average ratio of 0.16 of a metric ton of tall oil pitch per metric ton of CTO (Cashman et al., 2015) (Table 5). Were there to be demand for biofuel from tall oil pitch, more of it could be distilled from CTO. Tall oil pitch could be combusted for process energy as well.

Table 6 shows export information for CTO, distilled tall oil, and tall oil pitch, as well as more general export information for refined tall oil fractions that were derived from CTO. Specific export information for the different derivatives, such as tall oil fatty acids and rosins, is unavailable. The amount of CTO derivatives exported from the United States represents 4.5%–5.2% of estimated CTO production.

Table 6. Estimate of crude tall oil and tall oil pitch exports from the United States to different regions and countries in 2017: CTO and DTO combined, CTO only, and tall oil pitch, in thousands of metric tons. The "CTO only" category represents CTO that also falls in the CTO+DTO category. Dashes represent categories where no data is publicly available. Source: Aryan and Kraft (2020).

	CTO+DTO	CTO only	Pitch	CTO Derivatives
Asia	~60–85	~31–42	~7–10	-
Europe	~180	~56–61	~75–80	-
South Africa	~9–10	-	-	-
Global	-	-	-	~45–52

Other byproducts

Crude glycerin is a unique byproduct to consider for fuel production, as it is a derivative of biodiesel production itself. When FOGs are combined with methanol, biodiesel and glycerin are produced. We calculate the annual amount of crude glycerin produced in the United States based on the ratio of crude glycerin to biodiesel and 2019 biodiesel production (GREET, 2018; U.S. Energy Information Association, 2020) (Table 7). Changes in supply will vary with changes in biodiesel production; in general, as biodiesel output in the United States continues to expand, we expect production of this byproduct to increase as it has in the past (Figure 7). It is unlikely that the United States will import or export crude glycerin because it is a low-value product. It is more likely that higher-quality, refined glycerin will be traded.

Table 7. Current supply, production trends, use in transport fuel, imports and exports, and major data sources for crude glycerin, manure, and food waste. Units are thousands of dry metric tons, unless otherwise noted.

Byproduct	Current Supply (thousands of metric tons), unless otherwise noted	Production Trends	Current Use in Transport Fuel	Imports	Exports	Existing Uses (and Likely Substitutes)	Major data sources
Crude glycerin	610	Increase	Likely close to 0	Likely 0	Likely 0	Animal feed (corn), dust suppression (e.g., chlorides)	Oleoline (2012)
Manure	See Table 8	Increase	Close to 0	0	0	Biogas (grid electricity or natural gas), fertilizer (synthetic fertilizer)	Skaggs et al. (2018); U.S. DOE (2017); USDA ERS (2019a)
Food waste	4,900	Increase	Likely 0	0	0	Biogas (grid electricity or natural gas), compost (synthetic fertilizer)	Skaggs et al. (2018); U.S. DOE (2017)

Traditionally, crude glycerin is refined into a pure form and used in food, pharmaceuticals, and cosmetics. However, the expanding biodiesel industry is flooding the market with crude glycerin and lowering its market value. Crude glycerin derived from UCO in particular is harder to refine. Consequently, crude glycerin from biodiesel production is generally not being refined and instead is sold for a variety of alternative uses (Farm Energy, 2019; Oleoline, 2012). Here we do not describe alternative uses for refined glycerin; see Malins (2017) for more information on refined glycerin.

In 2012, 327,000 metric tons of crude glycerin went to what Oleoline (2012) called "disposal" applications, representing about 80% of total production that we estimate for that year. Oleoline reports that this disposal is "mostly" for use in animal feed and dust suppression. We assume that livestock feed represents 380,000 metric tons, or 80% of crude glycerin's disposal applications, while dust suppression represents 95,000 metric tons, or 20%. Dust suppression is for unpaved roads, a small percentage of roads in the United States (Jones et al., 2013).

For dust suppression, crude glycerin is primarily used in the western and southwestern United States, where dust worsens air quality. Other substitutes include chlorides, resins, clays, and oily products such as polyvinyl acetate and styrene butadiene resins (Yan & Hoekman, 2012; Skorseth & Selim, 2000). In livestock feed, glycerin has been found to be effective for pigs and broiler chickens, and it could also be an effective supplement for cattle (Farm Energy, 2019; Ledbetter, 2012). Since corn is generally the least expensive livestock feed ingredient with elastic supply and crude glycerin is similar nutritionally to corn grain, we assume that the most likely substitute for crude glycerin in livestock feed would be corn (Malins, 2017; Searle, 2019).

The fate of the remaining 20% of crude glycerin is unclear. It is possible that it is burned on-site for energy, in which case it would be combusted in diesel generators. The substitute for this use would probably be diesel fuel (Voegele, 2009). Other potential uses of crude glycerin are thermochemical and biological processes, including the production of propylene glycol; hydrogen via steam reforming; and fermentation into citric acid, 1,3-propanediol, or industrial ethanol. Industrial ethanol is used in producing chemicals and other materials besides fuels, as well as other chemicals (Ciriminna, Pina, Della, Rossi, & Pagliaro, 2014; Quispe, Coronado, & Carvalho, 2013). The most likely substitute material to produce other chemicals through fermentation would be corn or some other high-carbohydrate resource such as molasses. It can also be composted or anaerobically digested to produce biogas, which would probably be burned on-site to generate electricity and process heat; in this case, the most likely substitute would be grid electricity (Farm Energy, 2019).

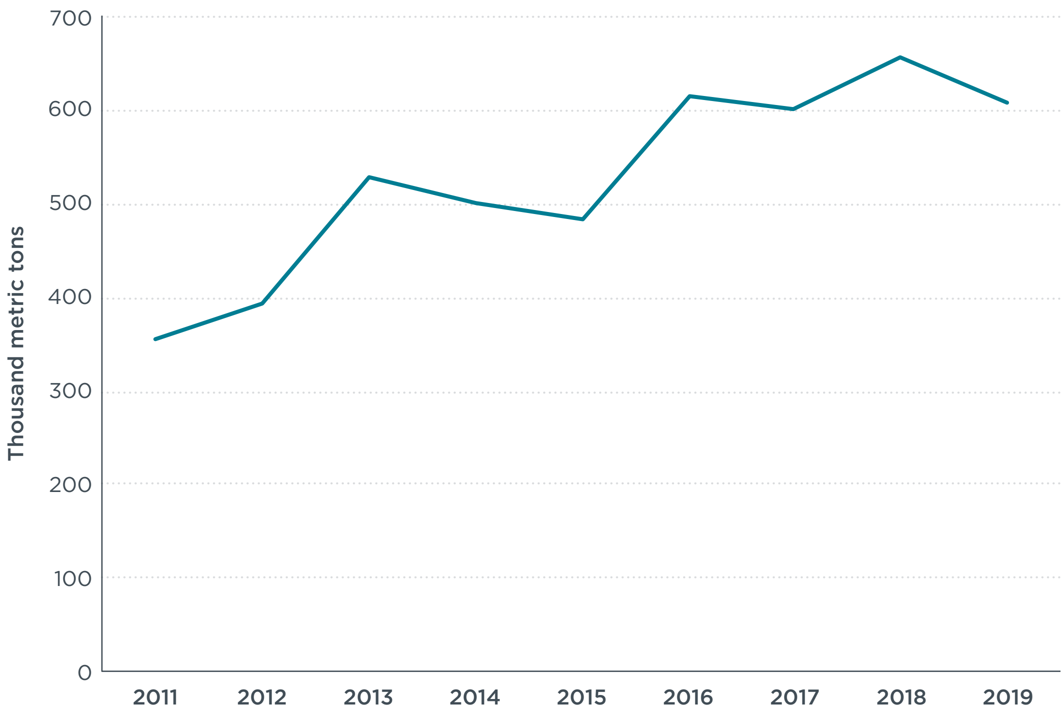

Figure 7. Crude glycerin production in the United States in thousands of metric tons.

Anaerobic digestion is a mature technology that uses wet feedstocks, such as livestock manure and food waste, to produce biogas. Biogas is a gaseous mix of 50%–60% methane, with much of the remaining volume including CO_2, volatile organic compounds, and trace impurities. The most common use of biogas is combustion on-site to produce electricity and process heat. It can also be cleaned and compressed into biomethane for injection into the gas grid, where it could be used in compressed natural gas vehicles, for example. Biogas has impurities that must be removed, including hydrogen sulfide and water vapor. Hydrogen sulfide is of particular concern because it can corrode engines (Lukehurst & Bywater, 2015).

Table 8 shows the potential for producing biomethane from cattle and swine manure for energy to be used in on-site combustion or cleaning and compressing for grid injection, as reported by the EPA in the annexes of the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (U.S. EPA, n.d.-b). Table 8 includes biogas that could be produced only from cattle and swine manure because the high nitrogen content in poultry manure inhibits biogas production (Einarsson & Persson, 2017). There are a few digesters in the United States where the sole or primary feedstock is poultry litter. These machines must deploy strategies to maintain a low ammonia concentration, such as co-digestion with other feedstocks or diluting the litter (Markou, 2015).

Table 8 also includes the amount of biogas from manure that is currently used for either on-site energy or injection into the grid, which we estimate based on the AgStar Livestock Anaerobic Digester Database. This database lists anaerobic digester projects on livestock farms in the United States, although the list may not be exhaustive. Of the farms with operational anaerobic digestion, 116 report the end use as electricity or a mix of electricity and other uses. To calculate how much biogas is used to produce the amount of energy a digester is reported to produce (in kWh per year), we use a conversion factor of 85 kWh per 28 m^3, which we retrieve from U.S. EPA (2018b). We include a 65% conversion efficiency, factoring in methane loss from off-gassing and downtime. This conversion efficiency possibly also includes biogas that would be used to power the machine (U.S. EPA, 2018a).

For those farms where the biogas or electricity generated is not provided, we estimate the biogas produced annually by multiplying the values for volatile solids, or dry organic matter in the manure, for each kind of animal from U.S. EPA (n.d.-a) by the number of livestock on each farm, as well as the appropriate conversion factors from U.S. EPA (2018b) and IPCC (2006). We find that the current use of biogas from cattle and swine represents around 3% of the total potential if all the cattle and swine manure were digested.

Table 8. Potential for biomethane from cattle and swine manure, as well as total volatile solids, or dry organic matter in the manure, currently used for biogas production in thousands of metric tons and current use of biomethane from cattle and swine manure, in the United States in cubic meters. The primary use is combustion of biogas on the farm.

	Biomethane potential (million cubic meters)	Total volatile solids (thousand metric tons)	Current use of biomethane (million cubic meters)
Nondairy cattle	4,700	26	--
Dairy cattle	1,600	1,000	--
Swine	100	0.82	--
Total	6,400	1,000	200

Note: Current use is not available for individual livestock types because some digesters used manure from more than one livestock type.

An estimated 13.6 million metric tons of manure are anaerobically digested or land-applied, primarily as fertilizer, out of the 37 million dry metric tons of manure that are recoverable, taking into account collection, transfer, and storage (U.S. DOE, 2017). We estimate that 1.3 million metric tons of volatile solids from poultry, swine, and cattle are anaerobically digested each year to produce biogas, meaning that around 12 million metric tons of manure are applied only to land without use for energy. Approximately 5% of all U.S. cropland is fertilized with manure, with use dependent on both specific nutrient needs for crops as well as transport costs. Corn accounts for more than half of the land using manure, with the majority of the manure coming from nearby dairy and swine operations (U.S. DOE, 2017).

Digestate from anaerobic digestion can also be used as fertilizer. One study found that high copper, zinc, and manganese concentrations in digestates from livestock manure could pose problems for agricultural soils (Nkoa, 2014). However, Risberg, Cederlund, Pell, Arthurson, and Schnürer (2017) found that digestate can be as effective as pig slurry and cow manure for use as fertilizer because the digestate was not found to impede soil microbial activity. Koszel and Lorencowicz (2015) also found that digestate was an effective fertilizer for alfalfa.

As reported in the oil and fat byproducts section, production by weight of poultry, beef, and pork is expected to rise over the next 10 years. However, for beef, this increase reflects the increasing size of the animals, not because the number of animals is rising. At the same time, the number of dairy cows and pigs is expected to expand, but they contribute only 26% of the potential for biomethane from manure (USDA ERS, 2019a). Overall, it is unclear exactly how manure production will change in the future as a smaller number of larger beef cattle may produce more manure. The number of concentrated animal feeding operations is also rising, meaning manure will be stored at fewer farms and it will be easier to collect and use for anaerobic digestion (Skaggs, Coleman, Seiple, & Milbrandt et al., 2018).

The final material considered in this study is food waste. We assume that food waste only from commercial sources such as grocery stores, restaurants, and warehouse and distribution centers; institutions such as hospitals, universities, schools, and prisons; and industrial settings such as food processing and manufacturing centers could feasibly be collected for use in transport fuel (Table 7). Our estimate of 4.9 million dry metric tons of food waste is based on Skaggs et al. (2018). Their work was derived from the number of businesses and employees reported in 2012 County Business Patterns; institutional data including hospitals, educational, and correctional facilities; the Homeland Security Infrastructure Program; and ratios of food disposed per capita in such organizations. It is likely that the amount of food waste in the United States will increase as the population rises.

There is little publicly available information on how much food waste is used in transport fuels. Two projects in the EPA's AgStar: Livestock Anaerobic Digester Database (2019) list food waste as a feedstock for producing electricity and biomethane, which the researchers label "compressed natural gas." Forty-four operational projects in this database list food waste as a feedstock for co-digestion with manure and other materials for end use as energy, such as on-site combustion for electricity, cogeneration, or, in one case, full-time flaring.

Most food waste goes into landfills, totaling an estimated 8 million dry metric tons in 2013 (U.S. DOE, 2017). California, Connecticut, Massachusetts, Rhode Island, and Vermont have passed legislation prohibiting entities that produce large quantities of food waste from sending it to landfills (Schultz, 2017). One million dry metric tons of food waste are composted. There are several options for substitutes for compost, such as agricultural byproducts including manure and animal bedding, yard trimmings, sewage sludge, and industrial byproducts, but the supply of these resources is inelastic. Because it is typically a means of disposing of organic material, composting is a low-value end use of these materials, so it is unclear whether compost would actually be replaced by a substitute material. It is possible that synthetic fertilizer could be a substitute. At the same time, synthetic fertilizer does not provide all the same benefits as compost does in adding oil organic carbon to the soil, which improves water retention and supports biota that increase soil permeability. Therefore, where compost is not replaced and even when it is replaced using synthetic fertilizer, we would expect reduced agricultural crop yields. As for other uses, 140,000–240,000 dry metric tons of food waste go to food banks. In this case, the substitute would be increased primary crop production. Livestock feed accounts for 23,600–47,100 dry metric tons of food waste use. As we do for other byproducts, we assume the substitute material in livestock feed would be corn (U.S. DOE, 2017; Searle, 2019).

We also considered damaged crops that are left in the field but did not include this material in our study for lack of data. It is likely that the supply of damaged crops varies year to year due to changes in weather and the amount of crops that become infected with disease. It is possible that some damaged crops are consumed by livestock, but the quantity is unclear (Kadam and McMillan, 2003).

Conclusion

This paper provides publicly available information for many byproducts, wastes, and residues, with a general focus on the United States: supply, trends and changes in supply, amounts currently used in biofuel, and trade information. We address substitutes for current uses of these byproducts to help identify potential displacement effects for future displacement analyses. A sister study discusses methodologies to estimate displacement emissions of wastes, residues, and byproducts used in biofuel, based on the data provided in this paper (Pavlenko & Searle, 2020).

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