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Indirect greenhouse gas emissions of molasses ethanol in the European Union

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Introduction

On November 30, 2016, the European Commission (2016c) published a proposal to the Council of the European Union (EU) and the European Parliament to recast Renewable Energy Directive (RED) 2009/28/EC (European Parliament & Council of the European Union, 2009), which will expire at the end of 2020. The proposed new directive (henceforth referred to as RED II) would enter into effect on January 1, 2021. Fuel suppliers would be required to include a minimum share of energy from advanced alternative fuels produced from non-food sources, including feedstocks listed in Annex IX of the directive. The target for advanced alternative fuel in transport increases to 6.8% of transportation fuel consumption by 2030.

The list of feedstocks in Annex IX of the directive is separated into two parts: Part A lists a series of feedstocks for the production of advanced biofuels, including algae, bio-waste from households and industry, industrial and agricultural residues, and energy crops. Part B includes three conventional low-carbon biofuel feedstocks, the use of which in biofuel has already been commercialized: used cooking oil (UCO), animal fats, and molasses. Within the mandate, the contribution from biofuels and biogas produced from feedstocks included in Part B of Annex IX is limited to 1.7%, to ensure a competitive advantage for advanced fuels in Part A of the Annex, which are at an earlier stage of commercialization. The greenhouse gas (GHG) emission savings from Annex IX biofuels would be required to be at least 70% for installations starting operation after January 1, 2021.

Within the Annex IX, Part B in the proposed RED II, molasses is defined as follows:

> “Molasses that are produced as a by-product from of [*sic*] refining sugarcane or sugar beets provided that the best industry standards for the extraction of sugar has been respected.”

Molasses was not listed in Annex IX in the previous version of the RED, although EU member states had the option to add feedstocks to this list and allow the amount of molasses biofuel that is consumed to be counted twice toward their obligations under the RED (called *double counting*). France is the only country in the EU that added molasses to the list of advanced biofuels, although without applying double counting (Ministère de l’Environnement, de l’Énergie et de la Mer, 2016; Vierhout, 2016).

Diverting waste, residues, and byproducts from their current uses to produce biofuels can be associated with significant indirect GHG emissions (ICF International, 2015). So far, diversion effects have not been accounted for in biofuels regulation, in the EU or elsewhere. Considering that the EU is looking to promote advanced biofuels from waste, residues, and byproducts, such effects should be taken into consideration in assessing GHG emissions.

In this context, the purpose of this paper is to assess the market and GHG impacts of molasses diversion to fuel use, and determine if it would meet the 70% GHG reduction threshold of the RED II. We describe the production and use of molasses globally and in the EU to understand the indirect effects of promoting molasses as a feedstock for biofuel. We also review literature on the GHG impacts of biofuel production from molasses, and conduct a displacement analysis to assess the indirect GHG emissions of molasses ethanol in the EU.

Sugar refining and production of molasses

The production of refined sugar involves three main phases: harvesting of sugar crops, production of raw sugar in a raw sugar factory, and refining of raw sugar into white sugar in a refinery (FAO, 2009). The two major sugar crops globally are sugar beet and sugarcane. Sugar beet is grown

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in temperate regions, and sugarcane is grown in tropical and subtropical regions. Approximately 20% of the world's sugar production comes from sugar beet, and 80% comes from sugarcane. In the EU, the majority of sugar is produced from sugar beet, and a small quantity is produced from sugarcane in overseas territories (European Commission, 2014).

The basic processes for sugar production are detailed in Figure 1 for sugar beet. The processes are similar for the production of sugar from sugarcane. Beets are sliced and processed to produce a juice that is rich in sugar. This raw juice is purified and concentrated by evaporation of water, to produce *thick juice* (Armishaw, 2002; Südzucker, n.d.). Thick juice is then evaporated in vacuum pans and seeded with pulverized sugar to initiate the crystallization process. This results in the formation of sugar crystals suspended in syrup. A centrifugation process separates the sugar crystals from the adherent syrup. The crystallization of sucrose is carried out in multiple stages—typically three stages—and the separation products of each stage are usually identified by the letters A, B, and C (Krajnc & Glavič, 2009). The first stage yields Sugar A, and the run-off syrup that was separated in the centrifuges is called *Molasses A*. Molasses A still contains a large fraction of sugar, and the crystallization and separation process can be repeated, resulting in *Molasses B*. Molasses B can also be crystallized for additional sugar production. The remaining syrup is called *final molasses* (also called *Molasses C*, *blackstrap molasses*, *residual syrup*, *run-off syrup*, or *treacle*); it cannot be further crystallized for additional sugar production. Sugar obtained from the first crystallization Stage A is known as *raw sugar*, which can be refined into white sugar. Sugars obtained from the second and third crystallization stages can also be refined and sold.

In traditional sugar mills, intermediate molasses (types A and B) are used for additional sugar production as a result of their high sucrose levels, but they also can be used for other purposes, such as ethanol production (Castañeda-Ayarza & Barbosa Cortez, 2016). Final sugar beet molasses has an unpleasant taste, but final sugarcane molasses has a sweet taste and can be consumed directly (OECD, 2007).

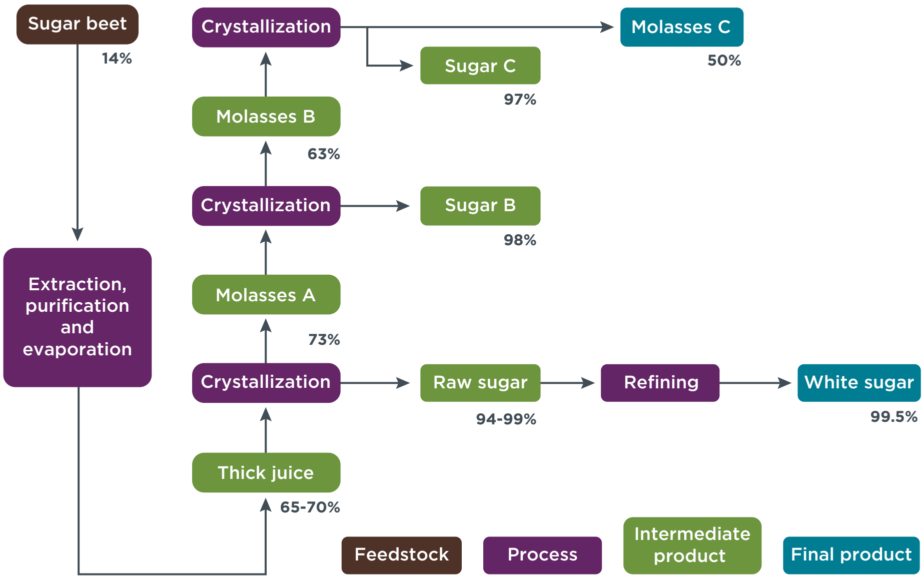

Figure 1. Simplified sugar production flowsheet. The sugar content of the various materials is indicated in percent of total mass. Adapted from Krajnc & Glavič (2009) and Morrison (2008).

Heuzé et al. (2015) noted that the type of molasses is rarely mentioned when molasses is traded. We have also observed this in most of the reviewed literature, where the type of molasses is not specified. According to Brander et al. (2009a), in practice all traded molasses is final molasses. For the purpose of this analysis, we also assumed that the sugar industry follows practices such that the maximum amount of sugar is extracted from molasses, and that all the molasses traded on the market is final molasses.

One major use of molasses is as a substrate in fermentation industries, for the production of alcohol and yeast. When molasses is used as a substrate in fermentation processes, a byproduct containing most of the protein and mineral content is produced; this is known as *vinasse* (also called *slop*, *stillage*, *distiller's wash*, *molasses spent wash*, or *dunder*) (Zali, Eftekhari, Fatehi, & Ganjkhanlou, 2017). Vinasse is thus a leftover fraction of molasses. Vinasse is mainly used in feed to improve feed intake and digestibility (Bilal et al., 2001; Iranmehr, Khadem, Rezaeian, Afzalzadeh, & Pourabedin, 2011) by providing protein and minerals (more on animal feed below). Because of its high potassium and nitrogen content, vinasse can also be used as fertilizer for arable crops, such as sugar beet, sugarcane, rapeseed, potatoes, and corn, but these uses are less common (Brouwers & Farinet, 1999; Johnson & Seebaluck, 2012; Krick, 2017).

Figure 2 shows average compositions of molasses from sugarcane and sugar beet (Heuzé et al., 2015), and of concentrated vinasse from sugar beet (Hansa Melasse, n.d.). The composition of molasses and vinasse depends on a number of factors, such as variety of crops, season of production, or processing technology; consequently, the chemical composition can show considerable variation (Carioca & Leal, 2017; Curtin, 1983; Dotaniya et al, 2016; Stemme, Gerdes, Harms, & Kamphues, 2005).

Uses of molasses

Final molasses from sugar beet and sugarcane is used mainly in livestock feed, yeast production, and to produce ethanol both for human consumption and for fuel. Other applications include use as a flavoring agent in some foods; as a component of material for de-icing of roads; and as a substrate for the production of biopolymers, bioemulsifiers, enzymes, ephedrine, antibiotics, and vitamins (Šárka, Bubnik, Hinkova, Gebler, & Kadlec, 2012, 2013). Such niche applications were not considered further in this study because data and statistics on these uses were lacking. Generally, sugar beet molasses and sugarcane molasses serve different markets: whereas sugarcane molasses is favored in the food and feed markets because of its better taste, sugar beet molasses is used predominantly for yeast and ethanol production and, to a lesser extent, as animal feed.

Molasses is used in livestock feed because of its nutritive and physical properties. It is mixed with other livestock feed, such as cereals (Archimède & Garcia, 2010; Comité National des Coproduits, 2012). Molasses can supplement poor quality feed as a source of minerals (e.g., calcium, sodium, potassium, magnesium, sulfur). Also, by stimulating the multiplication of bacteria in the rumen, molasses can also improve the digestion of fibrous feed (pastures and hay) and increase milk production (da Costa, de Souza, de Oliveira Simões Saliba, & da Costa Carneiro, 2015; Emanuele & Sniffen, 2014; Prairie View A&M University, 2012). Besides being used as an energy source for livestock, molasses is also used as binding agent in feed mills—to allow the production of pellets that are less likely to break down during transportation, and as an anti-dusting agent to reduce dustiness in fine-particle feeds (Heuzé et al., 2015; Lardy & Schafer, 2016).

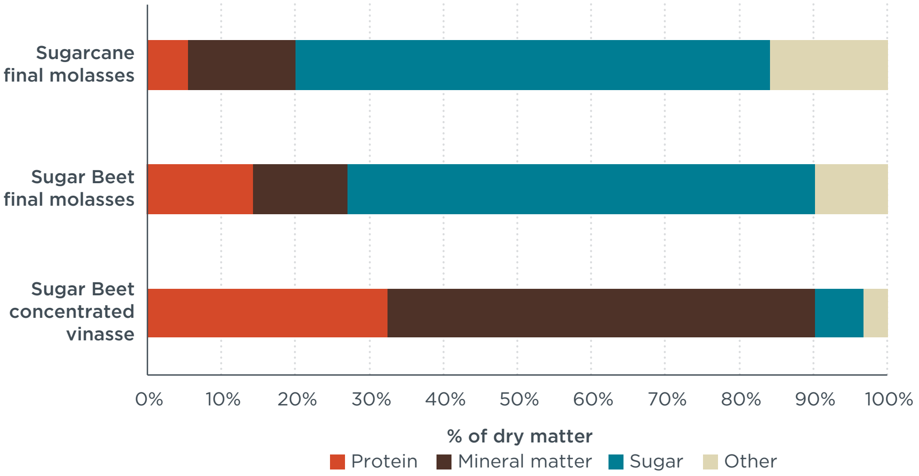

Figure 2. Composition of sugarcane final molasses, sugar beet final molasses, and sugar beet concentrated vinasse, in % of dry matter. Data from Hansa Melasse (n.d.), and Heuzé et al. (2015).

Molasses is also used as a nutrient substrate in fermentation industries to obtain a range of products, including baker's yeast, and various organic and amino acids (Bilal et al., 2001; FAO, 2001; UNIFERM, 2010). Bescond (2017) estimated that sugar beet molasses represents 90% of the substrate used by the EU yeast industry, and the remaining 10% is sugarcane molasses or glucose syrup (also called *sugar syrups*). Availability of molasses has been a concern for the yeast industry for several years—the main concern being that enabling biofuel production from molasses would result in an increase in the purchase price of molasses, and in a decrease in the supply of raw materials available (Bescond, 2017; COFALEC, 2006; European Parliament, 2017; Guichard, 2014). Telles (2008) estimated that the shortage of molasses caused by the start of government intervention in the EU sugar market (more detail below) led to molasses prices rising by 50% and a corresponding 10% increase in yeast prices in 2008.

Lastly, molasses is used as a feedstock for ethanol production, both for human consumption and for fuel. Raw juice, intermediate juices, molasses, and their mixtures are all suitable as feedstocks for ethanol production (Krajnc & Glavič, 2009). The choice of which feedstock is used to produce sugar or ethanol depends mainly on the market values of sugar and ethanol, and the optimal configuration of production outputs requires a techno-economic assessment of costs and benefits (Halasz, Gwehenberger, & Narodoslawsky, 2007; Johnson & Seebaluck, 2012; Krajnc & Glavič, 2009). In Brazil, factories have a flexible operational configuration that allows switching between Molasses A, B, and C and raw juice for ethanol production. In India, only Molasses C is used for ethanol production (Johnson & Seebaluck, 2012): because of a decision by the government of India, sugarcane raw juice cannot be used for the production of bioethanol because of possible impacts on the food production of the country (Ministry of Petroleum & Natural Gas, 2015). Using mathematical modeling to assess the economically optimal strategy for co-producing sugar and bioethanol, Krajnc & Glavič (2009) found that the margin between the optimal strategies for sugar and/or ethanol production is very slim: depending on the prices of sugar and ethanol, situations arise where it is more profitable to divert Molasses A, Molasses B, or thick juice to ethanol production.

Because the optimal strategy for the production of sugar and ethanol depends mainly on the market prices of these commodities, it is difficult to assess the extent to which the inclusion of molasses in RED II will have an impact on sugar and molasses production in the EU. Further promoting molasses as a feedstock for bioethanol could lead to a reduction in the amount of molasses available for the other sectors, an increase in the price of molasses, and eventually a reduction in the production of sugar, because there is a potential risk that sugar refiners would deliberately modify the production process to increase the sugar content of final molasses, or directly divert higher grade molasses such as Molasses A and B to bioethanol distilleries.

The European Commission's language on molasses in RED II includes the condition that the best industry standards for the extraction of sugar should be respected (European Commission, 2016c). However, it gives no indication on what the best industry standards for the extraction of sugar are. To our knowledge, there is no formally defined industry standard of best practices related to the extraction of sugar in or outside of the EU. If the initial intention of the European Commission is to prevent sugar refiners from deliberately increasing the sugar content of molasses, it appears that such language would not be sufficient. A more realistic safeguard could include specific recommendations, for example, a maximum amount of sugar content in molasses on a dry matter basis that is used as raw material in bioethanol distilleries.

Existing markets for molasses

WORLD MARKET

The global production of molasses (from sugarcane and sugar beet) amounted to 64 million tonnes in 2014. Molasses is mostly used in the country of production, and about 10% of the world production is exported to the world market (6 million tonnes exported in 2014). The main producers are, in order, Brazil, India, Thailand, China, the EU, Pakistan, and the United States. The largest exporters are, in order, Thailand, India, Pakistan, Indonesia, and Australia (OECD & FAO, 2016). Figure 3 shows the global consumption of molasses and its consumption in the feed and biofuel sectors. OECD & FAO statistics (2016) do not specify what the other uses of molasses are, however it can be assumed that the third most important use is in the fermentation industry (bakery and brewery yeasts).

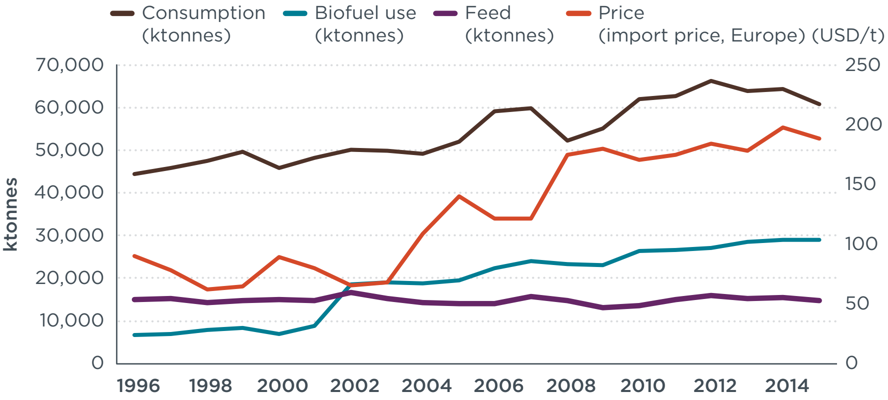

Figure 3. World molasses consumption and price (data from OECD & FAO, 2016)

The uses of molasses show considerable variation between countries. In Brazil, 84% was used for biofuel in 2014, while it amounted to 58% in India (OECD & FAO, 2016). The use of molasses for bioethanol globally has increased from 15% in 1996 to 45% in 2014, whereas the use in feed has remained broadly constant in absolute value (13 million tonnes to 16 million tonnes) (OECD & FAO, 2016). These values should be treated with caution because there are some discrepancies in the data.

EUROPEAN UNION MARKET

The EU is the world's main producer of beet sugar and the principal importer of raw sugarcane for refining. The availability and price of molasses have been significantly affected by the European sugar market. Under the current sugar regime implemented in 2006, the European Commission manages the EU sugar market by controlling the supply/demand balance. This is achieved through quotas to regulate production, combined with protection against imports (European Parliament & Council of the European Union, 2013). The EU's sugar production quota regime will end in September 2017, and EU sugar prices are expected to decline and become aligned with world market prices (Informa PLC, 2015). EU sugar output is expected to reach 6% above its 2016 production level by 2026, when the EU is expected to become a net exporter of white sugar (European Commission, 2016a; Terazono, 2014). This will also have an impact on the price and availability of molasses in the EU.

There are few publicly available statistics on the amounts of molasses used in the different sectors in the EU. Some authors have estimated the share of different uses of molasses in the EU; however, the estimates vary widely (see BIO-TIC, 2015; Brander et al., 2009a; COFALEC, 2007; Guichard, 2016). The following estimates are based on different sources and are the ones used in the displacement analysis below.

According to OECD & FAO (2016), the total amount of molasses consumed in the EU amounted to 4.5 million tonnes in 2015 (Figure 4), including 1.5 million tonnes of imported molasses. Molasses consumed in the feed sector amounted to 1.5 million tonnes, which is probably mostly imported sugarcane molasses (European Feed Manufacturers' Federation, 2016), and the quantities used in the other sectors are not specified by OECD & FAO (2016). According to COFALEC (2015), EU yeast producers buy around 0.8 million tonnes of sugar equivalent per year. Assuming that 90% of this amount is from sugar beet molasses (Bescond, 2017), and because sugar beet molasses is only around 60% sugar in dry matter (Figure 2), we can estimate that the yeast industry consumes about 1.5 million tonnes of sugar beet molasses per year. Based on those values, we can deduce that the quantity of molasses used for the production of ethanol would amount to about 1.5 million tonnes.

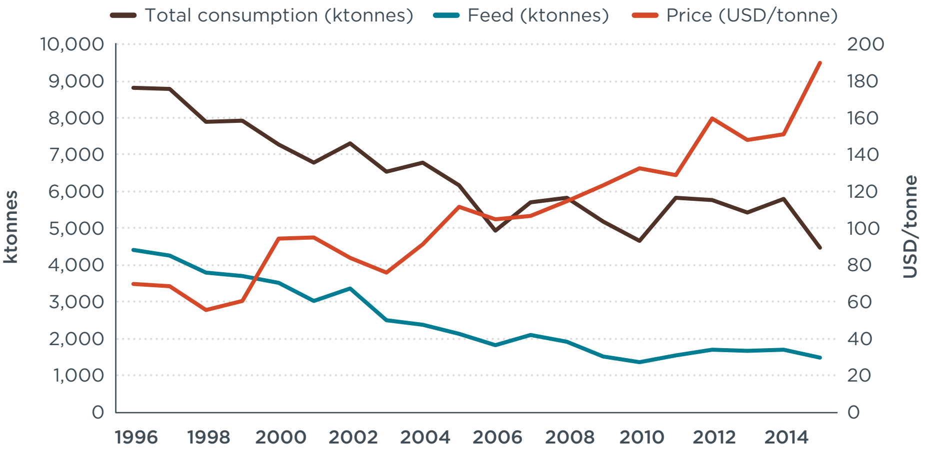

Figure 4. Molasses consumption and price in the EU (data from OECD & FAO, 2016)

BIOFUEL PRODUCTION UNDER THE PROPOSED CAP FOR ANNEX IX, PART B FEEDSTOCKS

In the European Commission's proposal for RED II (European Commission, 2016a), molasses is included in Part B of Annex IX, together with used cooking oil and animal fats. In the proposal, the biofuels and biogas produced from those feedstocks is limited to 1.7% of the energy content of transport fuels in road and rail. The projected business-as-usual energy demand in road and rail transport is estimated at 278 million tonnes oil equivalent (Mtoe) in 2030 (European Commission, 2016b). The total amount of molasses consumed in the EU in 2030 would probably not exceed 5 million tonnes, based on projections of the European Commission (2016a) and OECD & FAO (2016). This means that, if all the molasses consumed in the EU was used to produce ethanol by 2030, the amount of ethanol would be about 0.6 Mtoe, assuming a conversion factor of 227 liters of ethanol/tonne molasses (European Commission, 2010), or 0.2% of the energy content of transport fuels in road and rail. However, Searle, Pavlenko, El Takriti, & Bitnere (2017) found that, under the proposed energy target of the RED II, molasses ethanol would be more economically competitive than the other two feedstocks of the Annex IX, Part B, and so there could be an incentive to increase imports of molasses or molasses ethanol.

Lifecycle assessment

Assessing the GHG impact of a product requires methodological choices to carry out a lifecycle assessment (LCA). Existing LCA standards such as ISO 14040 (International Organization for Standardization, 2006) do not provide a rigid set of guidelines for calculating GHG emissions. Consequently, researchers have a range of choices in formulating a goal, scope, and methodology to assess the direct and indirect GHG impacts of a given product.

For product systems that generate a variety of different outputs, the GHG emissions must be attributed somehow among the multiple outputs, generally based on how much "responsibility" a given output bears for the manufacturing process. For example, soybean production generates both soymeal and soy oil; both of these valuable products bear some responsibility for the emissions produced in soybean cultivation and processing. LCA studies will typically allocate some soybean cultivation and processing emissions to soymeal and the remainder to soy oil. Similarly, some studies allocate a portion of the cultivation and processing emissions of sugar crops to molasses.

It is not clear, however, that this is necessarily the best approach to account for the effects of using molasses for biofuel. If we assign an allocated portion of upstream feedstock production emissions to molasses, we are in effect saying that increased use of molasses for biofuel will result in increased sugar production and thus the emissions associated with cultivating and processing sugar crops. A soybean farmer may decide to plant more soybean if there is an increased demand for soymeal, because soymeal accounts for a large fraction of the value of the soybean, but it does not seem likely that sugar farmers will plant more sugarcane or sugar beet because of an increased price of molasses.

The allocation approach helps answers the question: "How can I account for the emissions associated with producing molasses?" Instead, we could ask: "If I use molasses for biofuel, what will the net effect be on global markets and land use?" This is the type of question that indirect land use change (ILUC) modeling aims to answer, typically using global economic models. A simpler method that aims to answer the same question is a displacement analysis that predicts the market impacts of removing a biofuel feedstock from its existing non-biofuel uses. Hence, a displacement analysis estimates the additional indirect emissions associated with manufacturing substitutes for molasses' existing uses when molasses is diverted to biofuel production.

In the following sections, we review previous studies that aim to understand the lifecycle GHG emissions from molasses biofuel using either the allocation approach or a displacement analysis. We then conduct a new displacement analysis using the research presented above on the EU molasses market.

LITERATURE REVIEW OF GHG IMPACTS OF MOLASSES ETHANOL

This section includes a review of the literature on the direct and indirect lifecycle GHG estimates for molasses ethanol. The methodologies of the studies assessed in this literature review vary widely, with some allocating a portion of upstream emissions from sugar production, and others conducting a displacement analysis. Within the studies that allocate upstream emissions from sugar production, some include land use change emissions, while others only account for other direct emissions, such as fertilizer use and agricultural machinery. To facilitate our comparison, all of the GHG emissions values were normalized into a functional unit of gCO_2e per MJ (grams of carbon dioxide equivalent per megajoule of ethanol). Generally, there are three schools of thought on how to account for the full lifecycle emissions of molasses, although some studies only assess a portion of the full lifecycle calculation they are supporting:

- Account for only fuel production and transport emissions,
- Account for fuel production and transport emissions plus an allocated portion of upstream emissions of the primary sugar crop (upstream emissions may or may not include ILUC emissions from the sugar crop), and
- Account for fuel production and transport emissions plus indirect emissions from a displacement analysis (the displacement analysis may or may not include ILUC for the replacement materials).

Only one of the studies reviewed here and included in Table 1 assessed direct emissions for the production and transport of molasses biofuel. The Renewable Fuels Agency (2010) assessed imported molasses ethanol; this value does not include upstream emissions from sugar cane production, including only the transport of the feedstock, conversion of molasses to ethanol, and transport of the finished fuel (Table 1). The Renewable Fuels Agency (2010) estimated the direct emissions of ethanol molasses originating from Pakistan and South Africa as 77 gCO_2e/MJ and 87 gCO_2e/MJ for molasses, respectively. The conversion phase is the single highest contributor to the lifecycle emissions of ethanol, as both of these regions' conversion facilities are assumed to be powered entirely by coal combustion. However, the report found that conversion emissions are lower if the molasses is processed into ethanol in the United Kingdom, with a carbon intensity of 39 gCO_2e/MJ using coal and natural gas for power. The UK carbon intensity for feedstock and fuel transport emissions in this report was assumed to be zero, which is not realistic.

The California Air Resources Board (ARB) assesses direct carbon intensities for actual biofuel producers participating in the Low Carbon Fuel Standard program. Detailed information about these calculations is available for some historical biofuel pathways (ARB, 2016), but these pathways have been reassessed by the agency and the new carbon intensities are not disaggregated (ARB, 2017). In general, the pathways assessed by ARB appear to have substantially lower carbon intensities than the results published by the Renewable Fuels Agency (2010). For example, the legacy pathway application for Copersucar's facility Usina Barra Grande (ARB, 2015) estimated direct emissions from molasses ethanol production and transport to be 8 gCO_2e/MJ. Only 2 gCO_2e/MJ is attributed to ethanol production in this pathway because the ethanol conversion process is powered using sugarcane bagasse as a feedstock; bagasse is assumed to have no upstream emissions.

All of the other studies reviewed here focused on accounting for feedstock production emissions. Studies that estimated feedstock production emissions based on allocating a portion of upstream emissions from sugar production provided estimates ranging from 15 to 29 gCO_2e/MJ (Table 1). ARB also allocates a portion of sugar production emissions, but again, this detail is not provided for current pathways. In the legacy pathway application for Copersucar's Usina Barra Grande facility, ARB assessed total upstream emissions to be 21 gCO_2e/MJ (ARB, 2015). In addition, ARB allocated a portion of a coproduct credit of -12 gCO_2e/MJ for the use of bagasse to power the sugar mill as well as export bagasse-derived electricity to the grid; this is in addition to the use of bagasse to power the ethanol conversion process. Net upstream emissions are thus 9 gCO_2e/MJ for this pathway.

Three of the studies reviewed here that included allocated upstream emissions from sugar production did not include ILUC emissions for sugarcane (Gopal & Kammen, 2009; Khatiwada, Venkata, Silveira, & Johnson, 2016; and Tsiropoulos et al., 2014). ARB does add sugarcane ILUC emissions for all molasses pathways it assesses; the current value is 12

gCO_2e/MJ. Total emissions for all molasses ethanol pathways assessed by ARB, including direct emissions from fuel production and transport, allocated upstream emissions from sugar production, and ILUC, range from 38 to 54 gCO_2e/MJ (ARB, 2017).

Two studies reviewed here estimated displacement emissions rather than allocating a portion of sugarcane production emissions: Brander et al. (2009a) and Searle et al. (2017). These two studies used similar methodologies with some differences. The main difference is that Searle et al. (2017) accounted for molasses displacement from both livestock feed and yeast, while Brander et al. (2009a) only accounted for displacement from livestock feed.

Brander et al. (2009a) utilized an *order-of-dispatch* approach, which consists in determining which existing uses would be displaced first based on a number of factors, such as price, consumer preference, or regulatory constraint. The study determined that use of molasses in livestock feed would be displaced first, followed by yeast production, because there is a wide range of components used in the production of livestock feed and some flexibility to change the composition of inputs while maintaining energy and nutritional quality. On the other hand, the yeast industry does not seem to have such access to economically attractive alternatives to molasses. Furthermore, the authors could not find sufficiently detailed information about the use of molasses as a growth medium for yeast production to assess substitutes. In contrast, Searle et al. (2017) estimated average displacement effects, assuming displacement would occur evenly across livestock feed and yeast production; this is the *weighted average* approach.

Brander et al. (2009a) calculated the costs of alternative animal feed components based on metabolizable energy content. They then assumed that compound animal feed providers would be likely to source the energy components of their feed based on price, and identified imported molasses from Pakistan, barley, and wheat as the cheapest and most likely alternative sources of energy to replace molasses in compound feed. A substitution ratio was also calculated for the identified alternative feed components, based on the metabolizable energy content of the components relative to the energy content of molasses. The authors calculated a range of indirect emissions of 18 to 75 gCO_2e/MJ; the lower end of the range reflects replacement by imported molasses from Pakistan and the upper end of the range by UK wheat. The authors assumed that importing molasses from Pakistan would utilize molasses that otherwise would have been disposed of, but did not research other uses of molasses in Pakistan or verify that a significant amount of molasses is actually disposed of in that country.

Table 1 provides a summary of the research on the fuel carbon intensity impacts of molasses ethanol. The table shows how some of the studies analyzed only direct emissions from molasses ethanol conversion and transport, or allocated upstream emissions (direct with or without indirect emissions from land use change) or indirect emissions from displacement. These different approaches for estimating lifecycle emissions of molasses ethanol result in a wide range of values. Mainly, accounting for feedstock production emissions, whether through allocating a portion of sugar production emissions or through a displacement analysis, has a substantial impact on total lifecycle emissions compared to estimating fuel production and transport emissions alone. However, in most cases, these methodological differences have much less of an effect on the final result than the underlying assumptions behind each study, for example

Table 1. Literature review of GHG emissions of molasses ethanol.

Reference	Country/ Region	Fuel production and transport (direct) emissions (gCO_2e/MJ)	Allocated upstream (direct with or without indirect) emissions for sugar production (gCO_2e/MJ)	Displacement (indirect) emissions (gCO_2e/MJ)	Total (direct + indirect) emissions (gCO_2e/MJ)
Brander et al. (2009a)	UK			18–75	
Renewable Fuels Agency (2010)	UK	77–87 for imports; 39 for domestic			
Air Resources Board (2017) (current carbon intensities)	Brazil				38–54 (includes 12 for ILUC)
Gopal & Kammen (2009)	Brazil		15		
Khatiwada et al. (2016)	Indonesia		29		
Tsiropoulos et al. (2014)	India		24		
Searle et al. (2017)	EU			29–36	

whether assuming coal or bagasse as the energy source in fuel production.

DISPLACEMENT ANALYSIS FOR MOLASSES ETHANOL IN THE EU

Our literature review revealed that displacement analyses estimating the displacement impacts of molasses ethanol in the EU are scarce. Therefore, to estimate the indirect emissions associated with molasses use for biofuel in the EU, we develop a displacement analysis to estimate the emissions associated with manufacturing the materials that would be used to replace molasses. As described above, the most common non-energy uses of molasses in the EU are as feedstock for the manufacture of yeast and compound feed.

The displacement analysis presented here is similar to the one carried out by Searle et al. (2017), which assessed the GHG impact of several feedstocks in the Annex IX of the proposed RED, including molasses. The basic method is to identify the applications from which molasses would be diverted if it is used for biofuel, identify the replacement materials that would then be used in those applications, and estimate the GHG emissions resulting from increased production of those materials. This methodology also draws upon Brander et al. (2009b), although instead of an order-of-dispatch approach, this study calculates the weighted average displacement emissions across all other uses of the feedstock. We did not use the order-of-dispatch approach because it requires estimating the volumes of biofuel produced from a particular feedstock, and, following our estimates, the cap of 1.7% included in Annex IX, Part B of the proposed RED II would be large enough to allow the conversion of all molasses currently consumed in the EU.

Regional differences as well as sectoral differences are important to consider when assessing displacement emissions. The emissions from manufacturing a replacement for diverted molasses can differ based on the region or industry in question. In the case of molasses, there are important differences between regions in the share of use of molasses in the different sectors. Because such a level of detail is not available for regions outside or within the EU, we assessed the indirect impact at the EU level rather than differentiating between regions.

As molasses is diverted to fuel production, we assume that displacement occurs simultaneously across both non-biofuel uses of molasses relative to their proportions in the EU (i.e., a weighted average of both). Based on the amount of molasses used in the yeast sector (1.5 million tonnes) and in the feed sector (1.5 million tonnes) in the EU, we find that the proportions of molasses in the non-biofuel uses are 50% in yeast and 50% in feed. Each tonne of molasses used for bioethanol will therefore divert 0.5 tonnes of molasses from yeast production and 0.5 tonnes of molasses from compound feed.

In the production of yeast, glucose syrup produced from starch can be used as a substrate instead of, or combined with, molasses (Spigno, Fumi, & De Faveri, 2009). Due to lack of data on the direct emissions and origin of glucose syrup in the EU, we assume that molasses would be replaced by raw juice from sugar beet.

To understand the substitution effect on the compound feed sector, it is necessary to assess which potential feed is most likely to replace molasses. This depends on the price of the alternative feed and its composition. In reality, a precise estimate of the substitute feed would require complex modeling, because the substitution effects of a feed in a market are complex and depend upon a number of factors, including the amount, price, and quantities of other commodities available (Hazzledine, Pine, Mackinson, Ratcliffe, & Salmon, 2011). For this analysis, we determine substitutes on the basis of metabolizable energy (in calories per unit of mass).

We assume that compound feed producers would switch to other low-protein feedstocks based on their price per unit of metabolizable energy. Furthermore, we assume that vinasse, the liquid resulting from the production of ethanol from molasses, would be given to livestock. We assume that vinasse had no sugar, and that the protein and mineral matter present in molasses remains in vinasse. Considering a sugar content of molasses at 63% (on a dry matter basis, based on Heuzé et al., 2015), this means that the non-sugar compounds representing 37% of molasses are returned to livestock and are not associated with any GHG emissions. Put another way, 63% of molasses by dry weight would be converted to ethanol, and 37% would comprise vinasse; the vinasse fraction does not lead to indirect emissions. Consequently, the main impact of molasses diversion from feed to bioethanol production would be a reduced amount of energy in the total feed. This diverted energy content from molasses would be substituted by other crops. In the EU, the main sources of compound feed are corn, wheat, and barley, representing 22%, 21%, and 15%, respectively, of the total compound feed used in 2016 (European Commission, 2016b). In terms of price per energy, barley and corn are the least expensive and are thus assumed to replace molasses in feed. The average prices of barley and corn in 2016 in the EU were 0.047 and 0.049 €/Mcal, respectively, calculated from 143 €/tonne and 160 €/tonne (European Commission, 2017), and based on metabolizable energy contents of 3.0 Mcal/kg for barley and 3.3 Mcal/kg for corn (Hilton, n.d.). The proportion of corn and barley are taken from the current ratio of these two ingredients in EU livestock feed (European Commission, 2016b).

The direct emissions of sugar beet, corn, and barley are taken from typical values for the cultivation emissions for those crops included in the RED II proposal (European Commission, 2016a), and their indirect land use change emissions are taken from Valin et al. (2015). The conversion yields of ethanol from sugar beet, corn, and barley are taken from the European Commission (2010); the ethanol conversion yield for barley is taken as the ethanol conversion yield for coarse grains.

Following ICF International (2015), we select substitute materials with elastic supply, to avoid conducting second- and third-order displacement analyses. For example, an increasing demand for molasses in biofuel may lead to greater volumes of molasses imported to the EU from Brazil, where molasses would otherwise be used to produce ethanol. Because Brazil would still have a high demand for ethanol, the country would produce higher quantities of sugarcane than it would in the baseline scenario. The net result would thus be an increased use of sugarcane. Applying the approach recommended by ICF International (2015), we assume that molasses used for biofuel can only be substituted in other uses (e.g., livestock feed) by materials with a supply that can be increased. Such an approach would short-circuit a double displacement analysis by assuming EU molasses is replaced by sugarcane (in our analysis, we assume increased sugar beet production, but the results would be very similar for sugarcane).

Following Searle et al. (2017), we assume a 10% demand reduction in the non-biofuel uses of molasses. The reasoning behind this is that an increase in demand for a material due to a biofuel mandate will lead to an increase in the price of that material, and as a result, other users of the material will reduce their overall consumption. To illustrate: an increase in molasses demand for bioethanol will increase the price of molasses. In the feed sector, this will cause livestock farmers to switch to alternative compound feed such as barley, and the increase in demand of compound feed will result in an overall increase in its price, which will result in an increase in the price of meat products, for example. Demand for meat products will decrease, and this will result in lower livestock production, lower livestock feed consumption, and lower emissions associated with producing livestock feed. We assume the demand reduction effect to be 10%, because this is roughly consistent with the level of food demand reduction factored into ILUC models (reviewed in Malins, Searle, & Baral [2014]) and with estimates of indirect fuel use change (reviewed in Malins, Searle, & Pavlenko [2015]). This effect somewhat reduces the impact of material displacement.

The key assumptions of our displacement analysis are summarized in Table 2.

Table 2. Key assumptions for the displacement analysis.

Parameter	Assumption
Displacement of molasses in yeast production	Additional production of sugar beet, with direct and indirect emissions
Displacement of molasses in compound feed	Additional production of barley and corn, with direct and indirect emissions
Demand reduction for substitute materials	10% demand reduction

The resulting indirect emissions are calculated as 32 gCO_2/MJ. A sensitivity analysis is carried out through varying the following parameters:

- A 10% increase and decrease of the ethanol conversion yields (e.g., the default conversion yield for corn ethanol is 0.30 tonnes of biofuel per tonne of corn, and in the sensitivity analysis the yield varies from 0.27 to 0.33).
- The amount of molasses used in the yeast industry assumed to be 0.7 million tonnes instead of 1.5 million tonnes.
- The feed replacement composition changed to 100% barley or 100% corn.

The resulting indirect emissions range from 26 to 45 gCO_2/MJ.

To illustrate the net GHG savings for molasses ethanol, we add this result to the direct emissions for the conversion of molasses to ethanol and transport for the Copersucar facility described above (8 gCO_2e/MJ). Our estimate for the total lifecycle emissions of molasses ethanol is thus 41 gCO_2/MJ (with a range of 35 to 53 gCO_2/MJ). This represents a 57% (range of 43% to 63%) reduction of net GHG emission when compared to the fossil fuel comparator provided in the proposed RED II (94 gCO_2/MJ) (European Commission, 2016a).

Implications

The description of the production and use of molasses globally and in the EU in this study helps us understand that there are indirect effects of promoting molasses as a feedstock for biofuel. A literature review on the GHG impacts of biofuel production from molasses indicates that most studies do not account for displacement effects due to the diversion of molasses from its non-biofuel uses to bioethanol production. Our own displacement analysis assesses the indirect GHG emissions of molasses ethanol in the EU and finds a carbon intensity reduction of 57% (with a range from 43% to 63%) based on reasonable sensitivity of the input data. From this analysis, we determine that molasses ethanol would not meet the 70% GHG reduction threshold of the EC's proposed RED II regulation, if we account for all GHG lifecycle analysis emissions.

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