Dairy Management Inc.

Byproduct Feed LCA

Methods for Estimating Regional Byproduct Feed Greenhouse Gas Emissions and Water Consumption

PI: Dr. Rylie Pelton

LEIF
Lifecycle Environmental Impact Footprinting

March 2024

Goal

The objective of this work is to determine the greenhouse gas emissions and water consumption impact factors of 16 byproducts commonly used in the U.S. dairy industry, accounting for regional differences where possible, including:

- Almond Hulls
- Brewer's Grain Wet
- Canola Meal
- Cereal waste
- Citrus Pulp Wet
- Corn Cannery Waste
- Corn Distillers' Dry
- Corn Distillers' Wet
- Corn Gluten Feed Dry
- Cottonseed Whole
- Molasses - Cane
- Soybean Hulls
- Soybean Meal (Trt)
- Whey Acid
- Whey Condensed
- Whey Powder

Scope

Potential impacts are estimated for a cradle-to-processing gate system boundary (production-based) and cradle-to-dairy farm gate system boundary (consumption-based). The cradle-to-processing gate boundary accounts for material and energy inputs and emission outputs of crop production, transportation of feedstocks to byproduct processing, and byproduct processing. The cradle-to-dairy farm gate system extends the boundaries to additionally include transportation of byproducts to feed mills and feed milling processes where applicable, and transportation of feedstuffs to dairy farms.

Cradle-to-Processing Gate

(Production-based)

- Raw material production & transport
- Crop production
- Crop & material transport
- Byproduct production

Cradle-to-Dairy Farm Gate

(Consumption-based)

- Raw material production & transport
- Crop Production
- Crop & material transport
- Byproduct production
- Byproduct transport
- Feed milling & transport

For each byproduct feed, we estimate potential environmental impacts on a per kg of feed (as-fed) basis. We estimate total global warming potential (GWP) impacts (kg CO_2e) based on the IPCC 5th Assessment Report's (AR5) greenhouse gas equivalents using a 100 year time horizon, excluding biogenic carbon, and including climate carbon feedback. In this update, we further delineate GWP between emissions from land use change (LUC), and all other carbon dioxide equivalent emissions. We estimate water consumption (m^3), representing blue water no longer available to the hydrological system from which it was withdrawn due to evapotranspiration and water embedded in final products. Blue water consumption metrics provide a better indicator of potential threats to water scarcity than water withdrawals alone (Hoekstra and Mekonnen 2012).

The system boundary includes state-level production and distribution of domestic crops, byproducts, and byproduct feeds within the contiguous United States, as well as country-level imports when at least 5% of total US supply is imported. For each system boundary, we estimate the weighted average impact intensity for 12 subregions in the US, as selected by DMI, and described in Appendix tables A1 and A2.

Methods & Assumptions

Estimating Regionalized Impact Factors

Impact factors (total kgCO2e/kg feed, LUC-only kgCO2e/kg Feed, non-LUC kgCO2e/kg Feed, and m3 water consumed/kg feed) are estimated for the 12 US subregions using the following general procedure:

- We estimate differences in crop production emissions, land use change emissions, and water consumption based on yield variations across states of production, accounting for county level differences in domestic production practices where available (e.g., corn and soybean-based byproducts), and production differences across origin countries for imports.
- We estimate differences in emissions and water consumption attributable to byproduct production and feed milling processes based on:
    - Differences in electricity emission profiles across processing locations, based on intersections with the 26 subregional grids in the US and the associated unique grid mixes.
    - Differences in crop and byproduct sourcing regions across domestic and import regions of production based on estimated supply chains and associated emissions.
    - Differences in relative state byproduct production quantities by location, affecting regional production-based weighted average emissions profiles of production.
- We estimate differences in transportation emissions based on estimated supply chain sourcing models detailing origin-destination sourcing quantities by transport mode for imported and domestically produced crops, byproducts, and byproduct feeds.

We describe the details of these approaches below, along with the specific methods and assumptions used for estimating life cycle inventories for each of the byproduct feeds.

Supply Chain

For each byproduct, we developed an initial supply chain model linking regions of crop production to regions of byproduct processing, and regions of byproduct processing to dairy farm feed consumption regions, including feed milling as applicable. US Freight Analysis Framework (FAF5) origin-destination transportation data (Oak Ridge National Laboratory (ORNL) 2022) for both domestic and import supply chains of broad commodity categories, including 'animal feed', 'cereal grains', 'other ag products', and 'other food stuffs' (see Appendix Table A12), is used to estimate an initial sourcing and distribution model, resulting in supply chain linkages (routes) below:

- Import Crops: Origin Country ➔ Port State ➔ Byproduct Production State
- Domestic Crops: Crop Production State ➔ Byproduct Production State
- Domestic Byproducts: Byproduct Production State ➔ Feed Mill/Dairy State
- Import Byproducts: Origin Country ➔ Port State ➔ Feed Mill/Dairy State
- Feed Milled Byproducts: Feed Mill ➔ Dairy State

'Origin Country' refers to the foreign countries exporting crops or byproducts to the US, 'Port State', is the location of import prior to domestic distribution, 'Crop Production State' is the locations where relevant crops are produced, 'Byproduct Production State' is the locations where the byproducts of interest are produced, and 'Feed Mill/Dairy State' are the locations that purchase and consume the byproduct feeds.

Total available supply of domestically produced crops and milk are estimated based on state production from USDA Agriculture Census (2017) and USDA Agriculture Survey (2021, 2020, 2019 as available), and average county census data (2007-2017) as presented in Pelton et al 2021 for corn and soybeans (Pelton, et al. 2021). Total imports for each crop are based on the USDA World Agriculture Supply and Demand Estimates (WASDE) (USDA ERS 2023) with the distribution of imports across origin countries based on country level import data from the Global Agricultural Trade System (GATS) (USDA GATS 2022). Imported and domestically produced crops and milk are distributed from their points of origin to byproduct production locations based on each state's share of US byproduct production, as detailed in the life cycle inventory sections below for each respective byproduct.

For consumption-based footprints, we further estimate the supply chains for byproducts sent to feed mills prior to final consumption. We assume feed mills are distributed across regions and relatively near regions of dairy production, and as such, we distribute byproducts to feed mills in each dairy region based on the relative number of dairy cattle in each state within the region (see Appendix Table A2). After milling, byproduct feeds are assumed to be distributed to cattle within the same state for consumption. Byproducts that do not require milling are distributed directly from byproduct production locations to dairy farms for consumption.

For each origin-destination route permutation, we estimate the portion of travel by each mode based on transit mode distribution data from FAF5 by commodity group (Oak Ridge National Laboratory (ORNL) 2022), and then estimate total distances traveled by calculating the distance between centroids (Google Developers 2022) of origin, intermediary, and destination locations. Routes associated with supply chain origin-destination pairs contained within a single state are considered self-sourcing routes, with an assumed average distance of 80 km. We combine distances per mode per commodity per route with estimated tons transported along each respective route based on the supply chain defined above. We estimate total transportation impacts for each production and consumption region based on the total distance, quantity and mode of transport and the respective emission factors. For both import and domestic routes, we assume a 20-28 ton combination truck, a 65-ton cargo plane, and diesel-powered freight train. For water-based transport, we assume barge for domestic and transoceanic ship for imports.

Crop Inputs to Processing

In instances where data is available, we regionalize crop production impacts by capturing spatial differences in production emissions, water use and land use change emissions (e.g. corn and soy). Where crop production life cycle inventory data is limited to the national scale (e.g., GFLI, EcoInvent), we modify impact factors for each state of production based on state crop yields relative to the average yields assumed for national average impact factors. To do so, we first convert national average impacts (LUC only emissions, non-LUC emissions and water consumption) per ton to impacts per acre using national average yield data based on the USDA Agriculture Census (2017) and USDA Agriculture Survey (2021, 2020, 2019 as available), and then estimate state-level emissions by dividing by state-specific crop yields where available (e.g. Almond, Barley, Canola Seed, Cotton, Sugar Cane, and Sweet Corn) (USDA NASS 2022). Future efforts can make further adjustments based on differences in fertilizers used, irrigation, etc. where data is available, similar to approaches used in Pelton et al 2021, Kendall et al 2015, and others. Where possible, we leverage more specific subnational data available through literature or other external databases, such as in the case of almonds which are produced entirely in the state of California, or corn and soybean data which rely on county and state level estimates of production considering difference in fertilizers, N2O rates, cover cropping, tillage, LUC, irrigation, evapotranspiration potentials, etc.

For imported crops, country-level impact factors are based on the GFLI Products Database. For import countries with no available emissions and water consumption data, global average impact factors are applied. This occurs for 3.2% of barley imports, 0.9% of canola seed, and 22.1% of sugar cane imports (from largely Central and South American countries).

Electricity Inputs to Processing

We estimate the spatially-explicit impacts of electricity use in domestic byproduct production, as well as feed milling in instances where life cycle inventory unit process data for electricity usage is available in the literature. We combine estimated electricity inputs with spatial grid emissions profiles, as estimated based on the unique fuel mixes and associated LUC and nonLUC emissions and water consumption per fuel type from LCA databases (e.g. Sphere and EcoInvent), based on the estimated locations of byproduct production and feed milling, according to the supply chain model defined above. An area weighted average grid emission profile was calculated (representing the year 2020) for each byproduct production state based on intersections of eGRID subregions and their respective grid mixes (EPA Clean Air Markets Division 2020). Life cycle emissions for each subregion consider emissions from combustion, transmission and distribution losses and emissions embedded in the fuel mix from upstream processing and extraction.

Material and Fuel Inputs to Processing

Impacts are estimated for material inputs to domestic byproduct production and feed milling processes in instances where an applicable unit process life cycle inventory exists using impact factors from Ecoinvent, Sphera, and USLCI, delineating total, LUC only, and non-LUC emissions by material and fuel type, and prioritizing US national average production and sourcing mix data, with proxy country data used to fill data gaps as necessary (Wernet 2016, GaBi 2011, National Renewable Energy Laboratory 2012).

Byproduct Production

Spatial impacts are estimated and regionalized for byproducts based on 1) the weighted average impact factors of crop inputs, as determined through the supply distribution that links regions of crop production to regions of byproduct production, 2) the weighted average transportation emissions for crop inputs as described in the methods above, and 3) the weighted average emissions associated with byproduct production processes, including the area weighted average state emissions factors for electricity inputs. These spatially explicit impacts are then combined with the average impacts from materials and fuels used in processing.

For water consumption, though the majority of impacts occur from crop production phases, we use unit-process information on drying processes, water inputs, and moisture contents to estimate water consumption in processing where possible. For byproduct imports, impact estimates are based on country-level emission factors from GFLI and literature, and in instances where no country-level emissions data is available or where a country supplies less than 1% of total imports, a global average is applied (Global Feed LCA Institute 2023), affecting 0.8% of canola meal and 1.2% of molasses cane imports.

Feed Milling

For byproducts that require feed milling prior to consumption, spatial impacts are estimated and regionalized based on the weighted average emissions factors of byproduct inputs, including transportation, as determined through the methods above and the supply distribution model linking regions of byproduct production to regions of feed milling and consumption. We use the life cycle inventory for energy use per unit of feed milled as specified in Pehlken et al 2013 for feed milling processes, assuming the upper end estimates of natural gas and electricity use corresponding with a higher hardness pellet profile as preferred by cattle (Pehlken, Kirchner and Thoben 2013). We then apply the spatially-explicit grid emission factors for electricity use to estimate potential differences in milling operational impacts across the 12 regions.

Co-product Allocation

In LCA, the choice of allocation method often has significant implications on the potential environmental impacts of products, so in accordance with ISO 14040 guidelines, we avoid allocation to the greatest degree allowed by available data by partitioning the systems material and energy use between the sub-processes, enabling more accurate attribution of energy/material used for specific co-product processes. For true multi-product processes producing multiple co-products, or under data-limited circumstances, we use economic allocation approaches, with the exception of dairy co-products, where we allocate based on relative milk solids content in alignment with recommendations from the International Dairy Federation guidelines (International Dairy Federation (IDF) 2022). Specific allocation values attributed to byproducts and co-products are available in Appendix Table A13, according to USDA Economic Research Service, USDA Agricultural Marketing Service, LCA literature, and online feed databases, with assumptions detailed below for each byproduct. Note that future impacts of byproduct production may change as a result of different pricing structures for the various co-products.

Life Cycle Impact Analysis

The following sections provide details on the sources and adjustments made to the life cycle inventories and impact factors used to estimate subregional cradle-to-processing gate and cradle-to-dairy farm gate potential environmental impacts for each of the byproduct feeds.

Almond Hulls

Around 80% of the almonds in the world are produced in the US, with 100% of production coming from the state of California (USDA FAS 2022). We rely on the life cycle inventories of almond production and downstream processes in California provided by Kendall et al (2015) and provide estimates of inputs to almond orchards and co-product outputs over an assumed 25-year span. The study uses processor survey data representing approximately 15% of almonds processed in the state, and California grid mixes to estimate emissions from electricity use in processing. Almond cultivation and dehulling/deshelling operations produce several economically valuable co-products, including almond kernels, shells, hulls, and orchard woody biomass. The study presents total GHG emissions by gas type per kg of almond kernel, and we use economic allocation factors specified in the study to estimate total emissions from processing. We then apply the relative economic value for the hull fraction to estimate total emissions attributed to hulls per kg of almond kernel output, and the provided material balance, indicating the quantity of almond hulls produced per unit of almond kernel production, to estimate emissions per kg of hulls. We estimate land use change impacts by using California Statewide Almond Mapping surveys to determine the net change in standing orchard acres from 2003 - 2023, with approximately 1.36 million acres added over the timeframe (LandIQ 2023). . We estimate the associated change in carbon biomass stocks (MgC/ha) based on first estimating the carbon stocks associated with orchards and comparing to the lost carbon stocks from previous land uses. For orchards, we assume an average aboveground biomass of 6.9 MgC/ha (IPCC 2019), a total belowground biomass of 1.8 MgC/ha (based on root to shoot ratio of 0.26) (IPCC 2003), and total soil organic carbon (SOC) stock of 38 MgC/ha for HAC soils in warm temperate dry regions (IPCC 2003). We estimate the total carbon stock of previous land uses in California based on Pelton et al 2021 which suggest approximately 68 MgC/ha are lost from land conversion to agricultural uses. The net change in carbon stock is therefore estimated to be 21 MgC/ha. We then estimate the total LUC emissions attributed to the net increase in almond orchard area which is then divided by 20 to estimate the total annual LUC emissions. Total annual LUC is then further divided by the total annual hull production and multiplied by the hulls economic allocation factor to derive the total emissions from LUC/kg of hulls.

For water consumption, the study provides information on total blue water used across the 25-year span for each type of irrigation method deployed in California, including across sprinkler/micro-sprinkler, drip and flood irrigation systems, and the distribution of systems typically used. We use this information to estimate total water withdrawals in orchard production. We then use the state-specific return flow rates for agricultural production, as specified by the US geological survey, of approximately 23% to estimate the portion of water withdrawals not returned to the hydrological systems (Dieter, et al. 2018). We then divide the resulting total blue water consumption by the total quantity of hulls produced over the timeframe to estimate water consumption per kg of almond hull. Consumption-based estimates assume almond hulls are first sent to feed mills prior to final consumption.

Brewer's Grain Wet

Brewer's grains wet are a byproduct of the beer brewing industry, and due to the high moisture contents and perishability, are produced for domestic consumption entirely within the US with no imports. We identified locations and quantities of beer production using production facilities found to be widely distributed across the US (Alcohol and Tabacco Tax and Trade Bureau 2021), see Appendix Table A3. We use the US life cycle inventories provided in Dalgaard et al 2014, which specifies the crop, material, fuel, and electricity inputs of malting and brewing processes (Dalgaard and Schmidt 2014). Barley grains are used as the feedstock for malting processes, of which around 11% is imported, largely from Canada and Denmark (Appendix Tables A5 and A7). State-scale yield adjustments (Appendix Table A4) are made for the domestic portion of barley crop production (Appendix Table A5). We then use the methods specified above to estimate the weighted average production-based emissions from barley domestic production and imports, transportation, electricity, and material inputs used in malting and brewing processes.

Several co-products are produced in these processes, including malt and malt sprouts from malting processes, and beer and brewer's grain from the brewing process (Table 2.1). We use market prices (Appendix Table A13) to estimate the relative economic value of the co-product outputs and use them to allocate the total estimated emissions for each process (Appendix Table A2). The resulting brewer's grain is then further treated prior to sale as animal feed through drying processes that use electricity-driven mechanical presses to reduce the moisture content from an initial 80% down to 60% (Aliyu and Bala 2011). We assume the pressed water is returned to the hydrological system through wastewater treatment processes.

Consumption-based impact factor estimates assume brewer's grain wet feeds are first milled and mixed with other feed ingredients at feed mills prior to final consumption by cattle.

Canola Meal

Impacts of using canola meal in US animal feed diets depend largely on imports, as around 22% and 76% of US canola seeds and canola meals are supplied by imports, respectively (Appendix Table A5). The majority of canola seed imports are sourced from Canada, with domestic production occurring primarily in North Dakota, Montana, Washington, and Minnesota, together accounting for 99% of US canola seed production. We use GFLI specifying the LUC, non-LUC and water consumption impacts of canola seed production in the US and estimate emission across these states using state-scale yield adjustments based on the USDA 2020 survey using the methods specified above (Appendix Table A4).

For canola processing, primary areas of production occur in Minnesota, Missouri, North Dakota, Georgia, Illinois and Washington based on sales data, see appendix table A3 (Reference Solutions 2021). For canola meal imports, similar to canola seeds, the US sources around 99% from Canada. We rely on GFLI data for specifying the impacts of production and processing occurring within these countries. For domestic processing, we use the life cycle inventory presented in Obnamia et al 2020, which specifies hexane, natural gas, and electricity inputs, and canola oil and canola meal cake co-product outputs of the solvent extraction process, which is used predominantly in Canada and the US (Obnamia, MacLean and Saville 2020). We then use the methods above to estimate spatial impacts associated with these co-product production processes and use market prices to specify the economic allocation of impacts between the oil and meal co-products (see Appendix Table A13). In addition to these, the canola meal co-product outputs undergo additional desolventization and toasting processes. We use Mosenthin et al 2016 that specifies the steam and hexane vapor balance for the canola meal toasting process and estimate total natural gas required assuming a typical boiler efficiency of 80% (Mosenthin, et al. 2016). For consumption-based impacts, we assume canola meals are sent to feed mills prior to final consumption.

Cereal Waste

Production-based byproduct impact factors are estimated using Jeswani et al (2015), which specifies the life cycle inventory and impacts of cereal production in the US (Jeswani, Burkinshaw and Azapagic 2015). The life cycle inventory represents an average process encompassing several types of grain inputs, with rice grains accounting for 38% of ingredient impacts. For each ton of cereal product, around 80 kg of cereal wastes are produced, which are increasingly being used in the animal feed industry.

State distributions of cereal waste production (see Appendix Table A3) are determined by each state's share of US cereal production (Reference Solutions 2021). We rely on the GHG and water consumption estimates from Jeswani et al (2015) for each of the ingredient inputs, and combine with estimates of natural gas and water. We delineate LUC impacts by determining the portion of LUC from each ingredient used in cereal production based on LCA databases (e.g. Sphera, ecoinvent), and apply this percentage to the emissions estimated in Jeswani et al (2015). We then estimate the spatially-explicit impacts of electricity use using the methods specified above for each of the processing locations. We use current market prices for cereal and cereal waste products to estimate the relative economic value of the co-products and allocate impacts accordingly (see Appendix Table 13). For consumption-based impacts, we assume cereal wastes are sent first to feed mills prior to final consumption.

Citrus Pulp Wet

In the US, the majority of citrus processing occurs for the production of orange juice, with most orange production occurring in Florida and California (USDA GATS 2022, USDA FAS 2022). In juicing processes, around 60-65% of the initial mass is considered waste byproducts that are typically dried and sold as cattle feed (Nieto, et al. 2021). To estimate impacts of production, we rely on the economically allocated US impact factors from GFLI for domestic production of citrus pulp dry produced from juicing processes which specified LUC and nonLUC emissions (Global Feed LCA Institute 2023). We then use Teigiserova et al (2022), which specifies the life cycle inventories of hammer milling, pug milling, pressing, and heating processes associated with citrus pulp dry feed production, including inputs of citrus pulp wet byproduct, fuel, and electricity, along with Arthington (2008) which characterizes moisture content properties of citrus pulp wet and dry byproducts (Teigiserova, et al. 2022, Arthington and Pate 2008).

We estimate the amount of water removed in drying the citrus pulp wet products to produce citrus pulp dry feeds, through pressing processes which we assumed return to the hydrological system, as well as evaporator processes, which are accounted in total water consumption estimates. We then estimate the emissions from these drying processes using the average US grid mix, corresponding to the average conditions assumed in the GFLI dataset. Average impacts estimated for drying processes are then subtracted from citrus pulp dry impact factors to estimate US average impact factors for citrus pulp wet. To regionalize GHG emissions, we use the proportion of total impacts estimated to be attributable to the processing phase of 25% according to Coltro et al (2008), and adjust this portion based on differences in grid emissions profiles relative to the average US grid emissions profile across byproduct processing locations (see Appendix Table A3) (Reference Solutions 2021, Coltro, et al. 2009).

We assume citrus pulp wet byproducts are fed directly to dairy cattle, foregoing intermediate feed milling steps.

Corn Cannery Waste

Corn cannery waste byproduct feeds are produced from sweet corn cannery processes, with 98% of sweet corn production occurring domestically. Production-based byproduct impact factors are estimated using the life cycle inventory provided by Miller (2017), which specifies the total sweet corn inputs, and electricity inputs required for husking and cutting corn kernels off the cob at corn canneries (Miller 2017). We exclude energy use from blanching as these emissions are associated with the processing of the kernels and therefore are entirely attributed to the primary canned kernel products. For each cob of sweet corn, around 30-40% produces kernels for canning with the remaining part typically fed to livestock. Sweet corn production environmental impacts are based on emissions specified in Miller 2017, with spatial yield adjustments made for each state of production, and water consumption estimates based on field corn from Pelton et al (2021) (see Appendix Tables A4 and A5). We assume no LUC emissions are attributed to sweet corn due to the declining number of acres growing sweet corn in the US (USDA NASS 2022, Widmar 2023). We then use the methods specified above to estimate spatial impacts associated with electricity inputs used in processing using the state distribution of US canned corn production locations (see Appendix Table A3) (Reference Solutions 2021). We assume corn cannery waste is fed directly to cattle without the need for intermediate feed milling.

Corn Distillers' Grains - Dry (DDGS) and Wet (WDGS)

Production-based impact factors are estimated using Wang et al (2015), which specifies the life cycle inventory of corn ethanol production, including crop, fuel, and electricity inputs, and ethanol, distiller grain solubles (DGS), and corn distiller's oil co-product outputs (Wang, et al. 2015). In the US, more than 80% of ethanol producers separate the corn oil from the distiller grains, which are then either dried to 10% moisture content (dried distiller grains – DDGS) or directly fed to cattle at around 66% moisture content (wet distiller grains – WDGS).

We use the total energy consumption estimated in the study and subtract the subdivided energy inputs required for extracting corn oil from the distiller grains, for purifying ethanol products, and for drying DGS to estimate the portion of energy shared among each of the co-products. We assume the portion of total energy from natural gas versus electricity inputs specified in the study is similar to the proportions used in the shared processes, with energy used for corn oil extraction assumed to be powered by electricity inputs, and energy used for drying processes assumed to be fueled by natural gas inputs. We use the methods specified above to estimate the spatially explicit impacts of electricity use, and use average market prices between 2015-2017 for ethanol, ddgs and corn distiller's oil products to estimate relative economic values to allocate impacts of shared processes (Batres-Marquez 2018). For WDGS, we estimate that prices are approximately 35% that of DDGS products, based on weekly estimates across production states (USDA AMS 2023) resulting in the economic allocations presented in Appendix Table A13. We then use the relative economic value of corn oil and DDGS or WGS to distribute the energy associated with corn oil recovery between co-products. In addition to the energy used in production, we also include the impacts from chemicals used throughout the production process, which we rely on the estimates from Lee et al 2021 that specify a total unallocated impact of approximately 1.8 gCO2e/MJ ethanol (Lee, et al. 2021). Due to data limitations, water consumption impacts from chemicals usage are excluded, but are likely minimal compared to those from upstream corn production processes. For DDGS products, in addition to the above allocated impacts, we also include energy used specifically for drying the distillers grains, and use corresponding differences in moisture contents to estimate the associated total water consumption from drying (Pelton, et al. 2021, Lee, et al. 2021).

For corn inputs, we use the sourcing model and impact estimates from Pelton et al 2021, which is based on county-to-county supply chain models for corn inputs to dry mill ethanol facilities, and county-scale estimates of impacts from corn production and cropland expansion. County estimates consider differences in fertilizer, tillage, irrigation, conservation practices, and interactions with climate and soil conditions (see Appendix Table A8). LUC impacts are based on county scale estimates of land conversion and associated carbon loss. We use supply chains and impacts specified to then estimate the production weighted average impact factors for crop inputs from each state of production to each state of ethanol production. Consumption-based impact factors assume both DDGS and WDG are feed milled prior to final consumption, with distribution for DDGS based on county-to-county supply chain models from Pelton et al 2021, and WDG based on the methods described above using the state share of dairy cows to distribute feeds.

Corn Gluten Feed Dry

Corn wet milling processes produce a variety of co-products, including ethanol, dextrose, corn oil, corn gluten meal, and corn gluten feed wet products. Production-based impact factors are estimated using Kis et al (2019), which specifies the life cycle inventory of wet milling processes including crop, material, fuel, and electricity inputs and associated co-product and wastewater outputs (Kis, et al. 2019). We use the methods above to estimate spatial impacts of electricity use in production. Because detailed subdivided process information is limited, we use economic allocation to allocate aggregated impacts of the wet milling process to each co-product, based on current economic prices (see Appendix Table A13). In addition to the wet milling process impacts, we also estimate the impacts from drying corn gluten feed products. We estimate impacts of drying based on the initial moisture contents of the wet corn gluten feed, assumed to be approximately 60%, relative to the moisture contents of the dried corn gluten feed products at 88% (Erickson, et al. n.d., Heuze, et al. 2015). We assume drying processes use evaporators, where approximately 0.8 MJ/kg of water removed is assumed (Schutyser, et al. 2015), with the resulting total evaporated water accounted for in water consumption estimates. As in the case of corn used for WDGS and DDGS, we similarly rely on the sourcing model and impact estimates from Pelton et al 2021, which is based on county-to-county supply chain models for corn inputs to wet milling facilities, and county-scale estimates of corn production and LUC (Pelton, et al. 2021), see Appendix Table A8. County estimates consider differences in fertilizer, tillage, irrigation, conservation practices, and interactions with climate and soil conditions. We use supply chains and impacts specified to then estimate the production weighted average impact factors for crop inputs from each state of production to each wet milling state (see Appendix Table A3). We assume corn gluten feed dry products are sent to feed mills prior to final consumption, and use the methods specified above for estimating distribution to feed mill and dairy consumption regions.

Cottonseed Whole

Cottonseed whole is a byproduct of cotton ginning processes after the lint has been removed. Harvested cotton is transported to nearby gin locations where it is compressed, dried, and mechanically processed to separate lint from cottonseed. US cotton supply is 100% domestically sourced with production spread across 17 states, the majority coming from Texas (43.7%) and Georgia (10.9%) (USDA NASS 2022). We use the life cycle impacts of cottonseed production in these states from GFLI, which account for state-specific production practices and national average land use change. Some states however are excluded from that dataset, and in these cases, we estimate state-specific impacts by using state-level cotton crop yield data (see Appendix Table A4) from USDA to spatially adjust national average impact factors, affecting 8% of supply (USDA NASS 2022).

Within the ginning process, electricity is used for cleaning the cotton seeds, ginning, lint cleaning, bale packaging and material handling. We use estimates specified in Hardin and Funk (2012) to delineate the amount of electricity used per lint bale for each of these subprocesses (Hardin and Funk 2012). Because lint cleaning and bale packaging processes are specifically associated with the fiber co-products, we exclude these from our total electricity use estimates, and estimate the spatial impacts of electricity use based on the methods specified above given locations of cotton production. We similarly estimate the impacts from drying processes based on the inventory specified in Ismail and Baillie (2011), which describe approximately 101 MJ/bale. For each bale of cotton produced from the gin, around 700 lbs. of cottonseed whole byproducts are produced (Cotton Inc 2023) which we use to convert the unit processes to per kg of cottonseed whole. We then use the relative economic prices for cotton bales and cottonseed whole seed feeds to estimate the impacts allocated to cottonseed whole feed products (see Appendix Table A13). Because cottonseed whole feeds are fed directly to cattle, intermediate feed milling steps are foregone and consumption-based impact factors are estimated based on the methods described above, assuming direct distribution to dairy farms for direct consumption.

Molasses – Cane

Sugarcane processing involves the mechanical extraction of sugarcane juice, followed by a series of crystallization steps involving heating processes that produce molasses co-products. Molasses co-products often undergo several additional crystallization and separation steps until a final molasses, known as blackstrap or residual syrup is produced, where no additional sugar can be crystalized. After the final crystallization steps, the molasses products are often used as a mixing agent in feed mills for use in livestock feeds. In the US, around 73% of blackstrap molasses is domestically produced. We use the life cycle inventory of raw sugar processing activities specified in Meza-Palacios et al (2019), including crop, material, fuel, and electricity inputs, and the final raw sugar and blackstrap molasses co-product outputs (Meza-Palacios, et al. 2019). The inventory assumes bagasse byproducts are used within the sugar mills for thermal energy production, a common practice within the industry. We use the spatial distribution of domestic cane sugar production (Reference Solutions 2021) to estimate the spatial impacts of electricity use.

Sugar cane inputs and associated emission factors are dependent in part on imports, accounting for around 35% of total sugar cane supply in the US (USDA GATS 2022), with the remaining portion domestically produced from predominantly Florida and Louisiana (USDA GATS 2022). We use GFLI estimates for import countries where available, and global average estimates for import countries with no available estimates, which occurs for approximately 22% of the sugar cane imports (largely from Central and South American countries). Spatial adjustments are made for the domestic portion of sugar cane crop inputs (see Appendix Table A5), using state-level yield data from USDA NASS (see Appendix Table A4). We assume molasses products are sent to feed mills prior to final consumption.

Soybean Hulls & Soybean Meal (Trt)

Across the U.S., soybean crushers deploy a series of pretreatment, extraction, and refining processes to produce soybean oil, and several co-products, including soybean meals and soybean hulls, which are often used in livestock feeds as a primary source of protein and fiber.

Most commercial soybean oil production in the U.S. use solvent extraction processes instead of mechanical expelling processes due to the higher oil yields achieved (Demarco and Gibon 2020). We use the material and energy inputs and process flow information specified in Cheng (2017) for the hexane-based extraction process, which provides enough detail to estimate the life cycle inventories for each subdivided process across pretreatment and extraction steps, and subsequent soybean meal and soybean hull processing steps. During pretreatment, soybeans are first cleaned and conditioned for dehulling processes, producing soybean hulls and dehulled soybeans. The dehulled soybeans are then flaked to increase the surface area in order to maximize oil extraction. More than 60% of the electricity used in the crushing facility is used in pretreatment processes, with around 1.8 kWh/ton used in dehulling processes, and 9 kWh used in subsequent flaking processes.

Impacts from dehulling processes are allocated between soybean hulls and dehulled soybeans based on relative economic values of the combined soybean meal and soybean oil products versus soybean hull products (see Appendix Table A13). Impacts from flaking processes are instead attributed entirely to the soybean oil and meal co-products, along with extraction impacts, where soybean flakes are exposed to heat and hexane to extract the oils from the soybean meal cake. We allocate the impacts of these processes based on the relative economic value of the final soybean oils versus the soybean meals outputs.

After allocating the impacts of the shared processes, we also estimate the inventories and impacts associated with subsequent processing and treatments required prior to sale and use as livestock feed. For soybean meal, desolventization and toasting processes are used to remove the hexane from the soybean cake and increase the nutritional properties of the soymeal. The hexane is evaporated through direct and indirect exposure to steam. We use Kong et al (2019), which specifies approximately 265 kg of steam per kg of soymeal cake for the desolventization process, and Cheng (2017) which specifies the material handling and initial grinding of the soymeal for sale as feed (Kong, et al. 2019, Cheng 2017). Soymeal can be further treated to increase the digestibility of the feed through additional grinding to reduce particle sizes from the typical 1mm down to <.6mm (Lyu, et al. 2022). We use Lyu et al 2019 to capture the additional energy used for these subsequent grinding processes, assuming around 1.1 kWh/ton.

For soybean hulls, toasting processes are required to destroy the urease enzymes, which require heating the hulls up to 135 degrees (Kricka, et al. 2018) via use of natural gas inputs. To reduce the bulk density of the toasted soybean hulls for easier transport, grinding processes are deployed prior to subsequent feed milling (Lyu, et al. 2022). We similarly assume 1.1 kWh/ton of soybean hulls ground. We use the spatial distribution of soy crusher facilities and the associated grid profiles to estimate the emissions from electricity use in crushing.

Soybean crop production impacts are estimated using county-to-county supply chain models for crop inputs to soy crusher facilities from Pelton et al (2021), and associated impact estimates which use a combination of state and county level data reflecting differences in production practices and environmental conditions, across fertilizer use, N2O rates, tillage, LUC, and other conservation practices (see Appendix Table A8) (Pelton, et al. 2021). For both soybean meal and soybean hulls, we assume feeds are mixed in feed mills prior to final consumption, where county-to-county supply chain models are used for estimating sourcing regions for soybean meals (Pelton et al 2021), and the methods specified above using the relative state share of dairy cattle to estimate sourcing regions for soybean hulls.

Whey Acid

Whey acid is produced in large quantities from the fermentation of dairy milk to produce yogurt, cottage cheeses, and casein, with around twice as much whey acid produced for every unit of Greek yogurt produced. Due to the significant quantities produced and the lower protein content relative to sweet whey, whey acid can be used as a livestock feed to avoid wastewater treatment needs. We use Houssard (2020), which specifies the life cycle inventory used to produce yogurt and whey co-products, including raw milk, material, fuel, and electricity inputs and associated outputs of dairy processing activities, across subdivided processes including milk skimming, milk pasteurization, and fermentation (Houssard, et al. 2020). Skimmed milk and cream are co-products of the skimming process, whereas Greek yogurt and whey acid are co-products of the fermentation process which includes addition of lactic acid bacteria. Following production of whey acid, processing equipment undergoes final clean in place processes. When appropriate, impacts of multi-product processes are allocated to co-products and impacts of clean in place and total facility energy utility inputs which span all stages of production are allocated to all co-product outputs based on relative milk solids content, as recommended by International Dairy Federation guidelines. We use the methods specified above to estimate the spatial impacts of electricity production, and use recent US average cradle-to-farm gate milk emission factor estimates from the DMI 2020 analysis, and Henderson et al 2012 for water consumption impacts. We estimate production weighted average impacts across regions based on the state share of yogurt, casein and cheese production operations (Reference Solutions 2021), and distribute to dairy cattle production regions based on the methods specified above. Finally, we assume whey acid byproducts are mixed in feed mills prior to consumption.

Whey Condensed & Whey Powder

Condensed whey and whey powder co-products are produced from sweet whey obtained in hard cheese production processes, and commonly used in a variety of food and beverage applications, as well as mixed in livestock feeds as a high quality protein and energy source. Processing steps include milk handling and storage, milk pasteurization, cheddaring, whey pasteurization, reverse osmosis, and evaporation, with multiple co-products produced throughout. Whey powder products use an additional spray drying step to further reduce the moisture content. We use a combination of Tomasula et al 2013 for milk reception and storage, and pasteurization activities, and Aguirre-Villegas et al (2012) for subsequent cheese making activities, which together specify the life cycle inventory inputs and outputs applicable to both co-products, including milk, materials (e.g., chlorine, sodium hydroxide, nitric acid, etc.), fuel, and electricity inputs associated with subdivided dairy processing activities.

Cheese curds and sweet whey are produced from the cheddaring process, with sweet whey further processed to separate the remaining fat, which yield clarified whey and whey cream co-products. The clarified whey then goes through evaporators to reduce the moisture content which produces condensed whey, and a final spray drying further reduces moisture content to produce whey powder (Aguirre-Villegas, et al. 2012), which we account for in total water consumption estimates. Following the production of condensed whey and whey powder respectively, processing equipment undergoes a final clean in place process. When necessary, we allocate impacts of multi-product processes to co-products at each stage of production and allocate impacts of clean in place and utility energy useage are based on relative milk solids content, in alignment with International Dairy Federation guidelines for allocating impacts of dairy products. We use the methods specified above to estimate the spatial impacts of electricity use, and the mass balance information to estimate the quantity of water evaporated throughout the production process. For milk inputs, we rely on the US cradle-to-farm gate emission factors specified in Thoma et al (2013) and water consumption impact factors from Henderson et al (2012). We estimate production weighted average impacts across regions based on the state share of cheese production operations (Reference Solutions 2021), and distribute to dairy cattle production regions based on the methods specified above. Finally, we assume whey condensed co-products are mixed in feed mills prior to final consumption.

Limitations & Recommendations

While every effort was made to regionalize impacts based on the best data available under the timeframe and scope of the project, there are model and parameter limitations where future efforts could help reduce uncertainty of estimates and enhance regional distinctions, including:

- Water consumption estimates (excluding corn- and soy-based products) can be refined or adjusted in future estimates by incorporating differences in irrigation across production regions if unit process life cycle inventory data becomes available.
- Land use change impact estimates for corn and soybean crop inputs to DDGS, WDGS, Corn Gluten Feed Dry, Soybean Meal and Soybean Meal (Trt) currently represent impacts from crop expansion only. LUC impacts from agricultural inputs like fertilizers are anticipated to be insignificant and are therefore excluded. Land use change impact estimates for crop inputs to Brewer's Grain Wet, Canola Meal, Citrus Pulp Wet, Cottonseed Whole, and Molasses Cane currently rely upon national average LUC impact estimates from GFLI, and could be improved if higher resolution estimates of cropland expansion from associated crop inputs are developed or become available.
- Economic allocation estimates, where not referenced directly from LCA literature, rely on point-in-time market pricing, creating potential for variability in impacts attributed between co-products over time. Updating estimates to reflect average annual prices for byproducts across a 3-5 year timespan would increase stability of allocation estimates over the timeframe, with potential to change dramatically as demand for byproducts may expand in the future which may change market dynamics and relative values from co-products.

- Unit process inventories are not available for all crop and byproduct production processes, limiting delineation of subprocesses, and in some cases necessitating economic allocation of impacts or constraining the ability to spatially adjust impacts. Developing unit process LCAs for high-priority byproduct feeds will help facilitate regionalization efforts and increase accuracy of attributed impacts for future estimation efforts.
- Supply chain sourcing estimates can be refined through the application of least cost-optimization methods across all crop and byproduct flows, as is done for several corn and soy-based products that leverage existing efforts. For most byproducts, under the current scope of the project, we use origin-destination supply chain sourcing information to estimate state-level production- and consumption-weighted distributions, based on broad commodity categories. While this is a reasonable first step in capturing sourcing information, particularly as estimates are aggregated across the 12 U.S. subregions, future efforts could consider alternative methods for estimating supply flows specific to individual byproducts.

Appendix

See Appendix tables in 'DMI BYPRODUCT RESULTS_LUC Update_4.1.24.xlsx' file.

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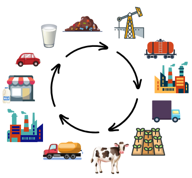

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Dr. Rylie Pelton is Founder and CEO of LEIF and Research Scientist of Industrial Ecology at the UMN Institute on Environment, specializing in methods to assess and improve the impacts of complex supply chains. Rylie holds a PhD in Industrial Ecology, PhD minor in Public Health, and M.S. & B.S. in Corporate Environmental Management from the University of Minnesota.

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