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# Life Cycle Assessment and Carbon Offset Potential for Cultured Milk Protein

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## EXECUTIVE SUMMARY

Cellular agriculture—the manufacture of animal products from cells rather than from traditional animal farming methods—is different from other meat and dairy alternatives in that it can provide both the sensory and functional properties of animal-sourced proteins without using any part of the animal (Waschulin and Specht 2018). The focal form of cellular agriculture in this paper is cultured protein, for which the main protein components of animal products are produced through large-scale fermentation by bacteria or fungi to generate a protein that is identical to its animal-derived counterpart (Waschulin and Specht 2018). By comparing a generic cultured milk protein life cycle assessment (LCA) to published LCAs on traditional milk protein, we attempted to estimate the difference in environmental impact and assess whether the greenhouse gas (GHG) emission differential might warrant carbon credit creation for cultured protein projects. Cultured milk protein production is a new and proprietary process, and so our analysis is based on data extracted from resources documenting similar production processes. We examined both the production of citric acid and the production of cultured meat or microbe-produced enzymes. The former is likely to underestimate the cultured milk protein production process's environmental impact, and the latter is likely to overestimate that impact. We assume that emissions from cultured milk protein likely fall somewhere in between the under- and overestimate,

and that actual production of cultured protein at-scale would more closely mimic that of our underestimate, based on industry research and emissions calculations for similar products. Our results show that if similar to citric acid production, cultured protein would likely have a lower carbon footprint, per kilogram of protein produced, compared to traditional milk. However, if cultured milk protein production is more similar to production of cultured meat protein, which seems less likely, some of our scenarios indicate the possibility of equal or increased emissions as compared to traditional milk protein production. The most environmentally friendly scenario of cultured protein production resulted in emissions of only 0.89 kg of $CO_2$ equivalent (eq.) per kg of protein produced, whereas the most emissions-intensive scenario indicated 146.5 kg $CO_2$ eq. In comparison, traditional milk production emits roughly 72 kg of $CO_2$ eq. per kg milk protein produced. We developed a hypothetical food-aid project that used cultured milk protein as a replacement for milk powder to determine the viability of developing carbon offsets to help finance the use of cultured milk for food in food aid. We determined that this hypothetical project could generate between 84,304 and 479,262 carbon credits, which are valued between $253,000 and $13.4 million USD, dependent on the GHG differential and credit sale price used.

## INTRODUCTION

With exponential population growth, the question of how to produce enough food to meet nutritional needs without accelerating already dangerous environmental side effects of traditional agriculture is increasingly important. Moreover, populations are rapidly urbanizing, and growing urban populations will have less access to traditional farming practices for food production (Satterthwaite et al. 2010). Typically, animal-sourced proteins—meat, eggs, and milk—have been an essential part of diets and provide the diverse nutrients needed for growth and development. The rearing and production of these animal-sourced proteins are resource intensive, however, and contribute approximately one-fourth of global GHG emissions (Alexandratos and Bruinsma 2012). As wealth continues to rise around the world, more people are incorporating animal-sourced proteins in their diet, further increasing the extent of animal agriculture and its impacts on the environment (Alexandratos and Bruinsma 2012).

Food sources that can provide the nutrients needed for a healthy diet while also having a smaller environmental footprint are critical to ensuring global food demands are met in a sustainable manner. Examples include diets promoting plant-based proteins such as lentils and nuts, as well as the meat substitutes derived from soy and other plants, like Beyond Meat or Impossible Foods' products. Cultured meat is another technology within the alternative protein sector, where cells are obtained from an animal and stable cell lines are identified which can then reproduce indefinitely—essentially enabling the growth of meat products in a laboratory (Specht and Lagally 2017).

Cellular agriculture can provide both the sensory and functional properties of animal-sourced proteins without using any part of the animal (Waschulin and Specht 2018). In one form of cellular agriculture, the main protein components of animal products are produced through large-scale fermentation by bacteria or fungi to generate a protein that is identical in both function and sensory properties to its animal-derived counterpart (Waschulin and Specht 2018). These proteins, hereafter referred to as cultured proteins, provide the same nutritional benefits as animal-source proteins, but due to their novel nature the environmental impact of producing these cultured proteins is not well known. While cultured protein has the potential to replace

a number of animal-derived proteins, this project focuses solely on milk protein because it is one of the more advanced cultured protein products being developed, is likely to be produced at scale within the next ten years, and because traditional milk production has relatively high GHG emissions.

Through this research, we set out to examine two primary questions related to cultured milk protein production:

(1) How does the environmental footprint of cultured milk protein compare to that of traditional milk protein (derived from cows)?, and

(2) If there is a significant difference in GHG emissions between production of cultured and traditional milk protein, would developing carbon credits for cultured protein production be profitable?

To answer question one, we conducted an LCA estimating the cradle-to-factory-gate production of cultured milk proteins to determine how the environmental impact of producing 1 kg of products similar to cultured milk protein compare to production of 1 kg of traditional milk protein. Life cycle assessment is a thorough and robust method through which the environmental impact of a process can be determined (McManus and Taylor 2015). It is often used to compare the relative environmental impact of comparable products. The environmental impacts included in the cultured protein model were greenhouse gas emissions, water use, and land use. The results were compared to a literature review of LCAs conducted on traditional milk production. For the cultured protein LCA we modeled the production of a casein-like protein, the primary protein found in milk (the protein content in milk is comprised of about 80% casein and 20% whey) (Davoodi et al. 2016). A pure cultured casein product will be identical to casein found in milk and could have a variety of uses such as a food additive, as a therapeutic or food-aid item, or, mixed with water and a form of fat, as a vegan milk substitute.

Our LCA included scenarios exploring how variation in cultured protein production geography (India vs. USA), energy source (coal, nuclear, natural gas), sugar source (beet, sugarcane, glucose), and efficiency of production affected its greenhouse gas, water, and land footprint. It is important to note that cultured proteins are novel products, and many cultured protein producers are still in the research and development phase and thus are not ready to share the details of their production process. Our LCA represents an analysis using data extracted from resources documenting similar production processes, the production of citric acid, which is likely to underestimate impact, and the production of cultured meat or microbe-produced enzymes, which is likely to overestimate impact. These were selected as the most similar to casein production based on limited information available from producers and assumptions about the process made from similarly produced food additives and enzymes. We assume that emissions from cultured milk protein likely fall somewhere in between the under- and overestimation, and that actual production of cultured protein at-scale would more closely mimic that of our underestimation, based on industry research and emissions calculations for similar products. However, because the process for producing cultured milk protein is not finalized and the product is not yet produced at scale (and the process is therefore not yet fully efficient), we include the overestimation to present possible emissions during early product development to show the full range of possible results.

For comparison to our cultured milk LCA scenarios we conducted a literature review of traditional milk production LCAs. We focused on the environmental impact of producing 1 kg of milk on a variety of scales and in different geographies. A world average from the Food and Agricultural Organization (FAO) was used as the baseline, with additional emphasis on studies in the target countries of Ethiopia, India, Senegal, and Vietnam. The selection of these target countries is explained further in the methodology, but they were primarily chosen to align with other analyses done in coordination with this study. While the literature review provided results for the production of whole milk, these results were transformed to examine the environmental impact of producing traditional milk *protein*, to be comparable with the results of our cultured protein LCA.

To address question two, we examined the GHG emissions differential between production of cultured and traditional milk protein to explore the possibility of developing carbon credits for these types of products. We created a hypothetical cultured protein "project" and used the GHG differential to calculate the potential number and value of carbon credits that the hypothetical project might produce. This was done to assess whether development of a voluntary carbon offsets protocol for cultured milk proteins is a viable venture to pursue for cultured protein producers to supplement revenue and bridge the gap between the costs of traditional milk and cultured milk products.

This study was part of a larger project that included exploratory scenario modeling to assess the nutrition, health, agricultural markets and production, and system level environmental impacts of cultured milk protein production (Herrick et al. 2020, in review).

### *Background on Carbon Credits and Offsets*

Carbon offsetting is a mechanism by which one party (person or company) pays someone else to reduce GHG emissions elsewhere in order to compensate for their own emissions (Kollmuss et al. 2008). Carbon offset projects (i.e., the activity that reduces GHG emissions) generate a reduction in GHG emissions or enhance carbon sequestration in ways that would not have occurred without the project in place. They do so by changing natural resource management or industrial processes. The differential between the emissions resulting from the verified carbon offset activity and what would have been emitted without that product or process in place represents a carbon offset. The amount of enhanced carbon sequestration or avoided loss amount represents a certain amount of carbon credits. To develop a sellable carbon credit for voluntary or compliance markets, carbon offsets must be verified using standardized procedures. In general, one carbon credit represents the reduction or removal of one tonne of $CO_2$ equivalent ($tCO_2$ eq.) (Hamrick and Gallant 2017). Carbon offsetting can provide an additional source of revenue for new technologies or practices. In theory, a cultured protein project could generate offsets if a cultured protein product's use replaces the use of an animal-sourced protein product that involves higher GHG emissions.

We spoke with representatives from The Gold Standard and Verra, two of the leading organizations for verifying and selling voluntary carbon offsets. Both organizations were interested in learning more about developing offsets for cultured protein projects but confirmed that no existing verification standard or offset protocol exists for such projects. This would mean that any cultured protein manufacturer or distributor wanting to develop offsets would need to first develop an offset measurement and reporting standard that would determine how net GHG

reductions would be measured for such a project. These conversations suggested that a carbon offsets protocol would likely be based on an LCA approach. The LCA described in this report was designed to help determine whether developing an offset standard for cultured protein production would be worthwhile. The scale of the differential in GHG emissions between animal sourced proteins and cultured proteins can help cultured protein producers determine if there is sufficient benefit of investing in protocol development and the transaction costs of getting carbon credits verified for sale in an existing marketplace.

Based on interviews with existing companies, it appears that no cultured protein manufacturers are actively working to develop carbon credits, although some have shown interest (Herrick et al. 2019). At this stage, the transaction costs for these companies, many of whom are still in the research and development phase, is too high. There was also a concern that production has not yet scaled, and that current offset calculations may not necessarily reflect final production processes.

### What Could Carbon Credits Look Like in the Context of a Cultured Protein Project?

Because calculating carbon offsets requires the comparison of GHG emissions from a business-as-usual scenario with emissions from a project scenario, there needs to be a defined "project" in order to develop cultured protein carbon offsets. In other words, simply releasing cultured protein products into the market likely would not qualify for credits because it would be very difficult to measure net change in emissions. It would be unclear whether the cultured protein product is replacing an animal sourced product in the market or is being purchased as an additional product by those who would normally not buy (or be able to buy) an animal-sourced protein.

In order to develop a defined cultured protein project that might be eligible for credits, the project developer would need to come up with some kind of project boundary. The following activities represent possible projects that may be eligible:

- Switching the protein source in a food-aid or therapeutic-feeding program from animal to cultured where it is not happening regularly in the marketplace
- Switching protein source in a food product from animal to cultured where it is not yet happening regularly in the marketplace
- A restaurant, caterer, or food supplier (e.g., airline food company, school lunch program) that switches from animal-sourced to cultured proteins in their production

## METHODOLOGY

### *Study Geography*

Ethiopia, India, Senegal, and Vietnam were selected as the target countries for the health and agricultural market analyses performed in conjunction with this study (Herrick et al. 2020, in review). They were selected based on their markets (including market size and country readiness), health need (including rates of stunting, wasting, and minimum diet diversity), and agricultural/environmental need (including water withdrawal and $CO_2$ emissions). The four target countries were selected based on their rankings within each attribute category and external feedback from project advisors. We focused on these countries to align our work with the outputs of the rest of the project. For the purposes of new LCA modeling, India was the only country with data

available in the ecoinvent database, thus it was the only country included in the cultured protein modeling scenarios. However, LCAs for traditional milk from the other target countries were included in the literature review where the information was available, to allow for comparison.

The LCA model scenarios were built using baselines that assume production in the western United States and use typical inputs for that region. The western U.S. was chosen for the baseline because that is currently where a majority of cultured milk protein production occurs. The target countries represent other production scenarios that are depicted through various combinations of energy or sugar source, dependent on the prominent resource input in each country. For example, sugar cane is the primary sugar source in all the target countries, whereas beet sugar is the primary sugar source used for this process in the baseline production country (the United States). These various models allow for estimates of the environmental impact if production moved to one of the target countries.

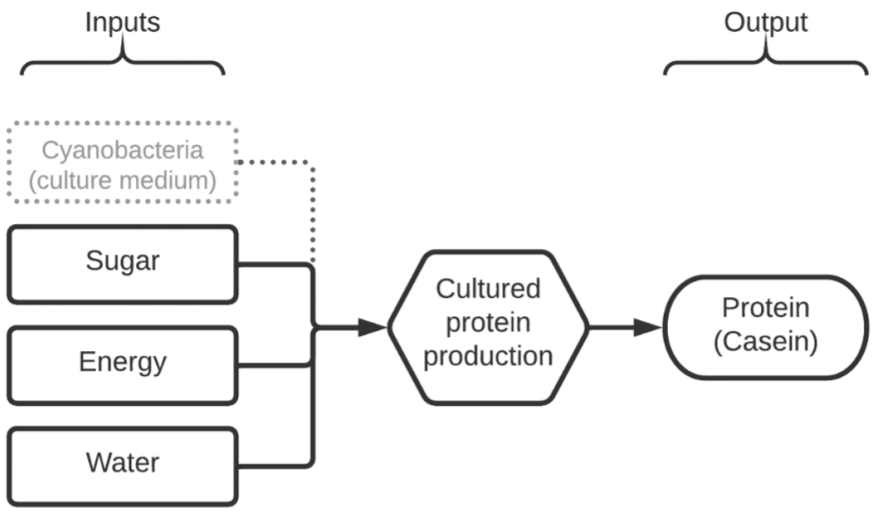
## *LCA – Cultured Protein Production*

This LCA assesses the relative GHG emissions, water use, and land use of cultured milk proteins relative to traditional animal source milk protein, using the assumption that cultured milk protein production is similar to other industrial fermentation processes. There are insufficient data to consider other environmental impacts. Creating cultured proteins is a novel technology so LCA input data had to be extrapolated from other similar processes that are more established. Assumptions had to be made regarding the inputs used and their amounts, what parts of the process can be omitted, and how other LCAs are conducted in order to make results comparable. Here, we lay out the methodology we used to develop our LCA and the assumptions we made related to the cultured protein production process and the input data chosen.

### Literature Review – Cultured Protein Production

A wide literature search was conducted to better understand the cultured protein process, the inputs and outputs, and the quantities used to produce a kilogram of casein, the specific milk protein being produced. Since the technology to produce cultured proteins is relatively new, very little information was available on this specific process. Therefore, we modeled the production process on what is used for LCAs of similar fermented products including citric acid, beer, cultured meat protein, and microbe-produced enzymes and used these to determine a system boundary. Figure 1 outlines a high-level overview of the system boundary.

**Figure 1. System boundary of our LCA**




*Note*: The type of sugar and energy input changes depending on the model scenario. Cyanobacteria culture medium is only used as an input in our high-end scenarios.

Our research into other similar production processes indicates that there are likely additional inputs beyond sugar, water, energy, and culture medium. These additions include other chemicals and reagents that are used to refine chemical processes taking place during fermentation. However, due to the fact that specific chemicals for cultured protein production are unknown and that their input amounts are relatively insignificant we have chosen not to include them in this exploratory model.

### Data Collection

Specific quantities for process inputs were extrapolated from LCAs on similar processes, including an early-stage sustainability assessment (ESSA) of fermented citric acid production (Becker et al. 2020), an LCA of Italian lager beer (Cordella et al. 2008), an LCA of cultured meat (Tuomisto and Teixeira de Mattos 2011), an early stage LCA for cultured milk (Steer 2015), and LCAs for microbe-produced enzymes (Nielsen et al. 2006; Kim et al. 2009; Feijoo et al. 2017). The assessment of citric acid production provided insight into the low-end energy usage of producing a fermented product and the LCA of Italian lager beer informed the quantities of water that are needed. The Kim et al. (2009) LCA gave an estimate of what a high-end energy use scenario might look like while the cultured meat LCA provided a high-end estimate of the amount of culture medium required.

### Data Assumptions

Data for the LCA model was supplied through the ecoinvent 3.6 database. While the database is robust and provided much of the information needed to conduct the LCA, some assumptions had to be made based on the availability and categorization of data within ecoinvent. These assumptions are noted below:

- Inputs
  - Without specific data and information on the cultured protein production process, we developed scenarios using two different baselines with different input assumptions to bound the lower and upper end of possible process impacts. More information on these baselines is provided in the Process Assumptions section below.
- Nuclear Power
  - The ecoinvent database contains data for both boiling water and pressure water reactors. Without a specific powerplant in mind, it could not be determined whether it was a boiling water, or pressure water, reactor. A brief search also showed that both boiling water and pressure water reactors are used in the production region (U.S. Energy Information Administration 2020). Information for a boiling water reactor was used for this analysis, as there wasn't a significant difference between the two systems.
- Sugarcane
  - For the scenario with cultured protein production in India, it is likely that sugar produced from sugarcane in India would be used. While the ecoinvent database contains some regionality in terms of where the product is sourced from, the only available options for sugarcane processing were data from Brazil, and an average of world data. We used the option with sugar production in Brazil.
- Beet Sugar
  - Average world data for beet sugar production was used for this analysis, due to lack of availability by region.
- Energy Transformation
  - In version 3.6 of the ecoinvent database, all energy is considered to be high voltage energy, as that is the output of powerplants. Since we assume production will be at industrial scale, which uses high-voltage energy, thus impacts associated with transformation of high to medium voltage were not required.
- Transportation
  - Transportation of inputs from their production site, to the cultured production site, was not considered. In our hypothetical scenario there was no reason to assume inputs would be coming from any particular geographic region. However, one scenario was modeled that assumed transportation of sugar from the eastern United States to the western United States to understand the impact that transport could have on the carbon emissions of cultured protein production.

### Software – openLCA

Our models were built in openLCA 1.9, using the ecoinvent 3.6 database and ReCiPe 2016, midpoint, hierarchist, impact assessment method. We chose this method because it produces the least uncertainty in the results, allows for greater interpretation of the environmental impacts

and tradeoffs, and uses a timeline that is most aligned with policy making. With the number of assumptions that we had to make, it was important to choose an LCA methodology that eliminated as much variability as possible. This database and impact assessment method were also chosen because of their ability to integrate seamlessly into the openLCA software.

### System Boundary

The system boundary included the upstream impacts of the three key inputs: energy, sugar, and water (Fig. 1). The system ends with the production of 1 kg of cultured casein. For sugar, upstream inputs include the growing, harvesting, and processing of agricultural products to create sugar. For energy, the upstream inputs include the operation, maintenance, and materials used in the power plant, as well as the fuel need to start the plant. Lastly, for water the upstream inputs include the operation of a conventional water treatment plant that produces water ready for distribution.

### LCA Database – ecoinvent

The database used to populate the openLCA software was ecoinvent version 3.6, which was released September 12, 2019. Of the multiple datasets included in the database, this project selected allocation at point of substitution (APOS), a system model that attributes burdens proportional to the process, rather than cut-off or consequential (System Models in Ecoinvent 3, n.d.). These system models dictate how the waste produced throughout a process are managed and where in the process the environmental burden of waste falls. For a process as simple as the one modeled for cultured protein, this plays a minor role, because there are not multiple levels of waste streams produced at various stages of the process. Additionally, the process was regarded as a system, in which the input and output data are aggregated to produce an aggregated life cycle result, rather than a unit process which considers the input and output of the smallest unit. These choices allow for the entire process to be analyzed together, while also understanding which parts of the process contribute most to each environmental impact.

### LCA Impact Assessment Method – ReCiPe 2016

To analyze the impacts of an LCA, an impact assessment method is required, and for this project, ReCiPe 2016, midpoint, hierarchist was used (Huijbregts et al. 2016). Impact assessment methods follow a basic structure, consisting of characterization, damage assessment, normalization, weighting, and addition. The only International Organization of Standardization (ISO) required component is characterization, which is the factor by which substances contribute to a specific impact category. For example, the characterization of $CO_2$ to climate change is 1, whereas the characterization factor of methane is 25. Every 1 kg release of methane is equivalent to 25 kg release of $CO_2$.

### Process Assumptions

For our LCA model, packaging was not considered at any point in the process given the uncertainty as to how these products will be packaged and marketed once they reach full-scale production. Packaging was sometimes included in the comparator LCAs that were included in our literature review, and those have been noted in the Traditional Milk Literature Review section.

We built two separate baseline scenarios to account for uncertainly surrounding the cultured protein production process. The low-end baseline uses estimates for input requirements that liken the cultured protein process to that of producing citric acid. Citric acid production was used as a substitute for cultured protein production because we learned that it has a similar production process based on conversations with cultured protein manufacturers. Though there are a few

different food additive products with similar production processes (e.g., rennet), we found that citric acid was the only product with readily available data that provided specific quantities of inputs during each step of the production process. However, citric acid is produced through a relatively simple fermentation process that breaks down existing molecules (rather than building new protein molecules from scratch). For this reason, we view this as a low-end estimate of the inputs required for a culturing process. Our high-end estimate of inputs was based on the production of microbe-produced enzymes and cultured meat. Culturing meat is a complex process that produces not just protein but all the cellular components and structures that make up animal muscle tissue (Specht and Lagally 2017). Microbe-produced enzymes can be more or less complex molecularly than casein but are certainly more energy- and resource-intensive than producing citric acid. These products therefore represent a high-end estimate for the culturing process. We do not believe that either of our baseline scenarios exactly represents cultured casein production, however, we do believe they represent reasonable bounds for the required inputs. We expect that actual production of cultured protein at-scale would more closely mimic that of our low-end baseline, based on industry research and emissions calculations for similar products. Through conversations with industry experts, we learned that to efficiently and profitably produce cultured protein at scale it is unlikely that a process represented by our high-end baseline would be feasible. However, we include it here due to the current uncertainty of what eventual cultured protein production will require. The quantities of inputs for our baseline scenarios are summarized in Table 1.

For the low-end baseline, the specific quantities of energy and sugar needed to produce 1 kg of casein were extrapolated from data in an early stage sustainability assessment (ESSA) for citric acid production (Becker et al. 2020). In order to deduce the quantities of inputs required for cultured protein production, inputs were aggregated for all the steps in citric acid production that are also relevant to cultured protein production (cultivation, biomass separation, and crystallization). A similar method was used to determine the water input data for cultured protein production, with information gleaned from an LCA of Italian lager beer (Cordella et al. 2008).

The high-end baseline was built assuming the energy and sugar inputs of a relatively intensive enzyme production process, and the culture medium inputs similar to those required to produce cultured meat. High-end baseline information was gathered from LCAs for cultured meat production (Tuomisto and Teixeira de Mattos 2011), a preliminary LCA on cultured protein (Steer 2015), and LCAs for enzyme production (Kim et al. 2009; Feijoo et al. 2017).

**Table 1. Summary of cultured protein inputs required for the production of 1 kg cultured casein for the low- and high-end baseline scenarios**

| Baseline | Input | Quantities | Source |
|---|---|---|---|
| Low-end | Energy | 21.165 KwH | Becker et al. 2020 |
| | Sugar | 1.07 kg | Becker et al. 2020 |
| | Water | 2.95 L | Cordella et al. 2008 |

| Baseline | Input | Quantities | Source |
|---|---|---|---|
| High-end | Energy | 58 kWh | Kim et al. 2009 |
| | Sugar | 60 kg | Steer 2015 |
| | Water | 2.95 L | Cordella et al. 2008 |
| | Cyanobacteria (culture medium) | 3.78 kg | Tuomisto and Teixeira de Mattos 2011; Tuomisto et al. 2014 |

The LCA model was developed with an output of 1 kg of casein, which is pure protein. Whole milk is a combination of fat, protein, and water, with protein ranging from 32–36 g per liter of milk (Davoodi et al. 2016; Haug et al. 2007). We assumed 33 g of protein per liter of milk for our calculations. Additionally, the protein content in milk is a combination of casein and whey (Davoodi et al. 2016). For this analysis, it was assumed that all the protein content in milk would be casein because the process of making cultured casein and whey is assumed to be the same.

### *Scenario Analysis and Model Building*

With the process and quantities of input and output identified, different scenarios for cultured casein production were examined. Table 2 describes all the scenarios modeled. The scenario and modeling processes were based on the data available in ecoinvent 3.6 and our understanding of the options available for each input. Beet sugar and natural gas were determined as the baseline sugar and energy sources because these were the prominent energy and sugar sources in the assumed region of production—the western U.S.

Each scenario uses either the low-end or high-end baseline input amounts described in Table 1. Each scenario differed from its associated baseline in terms of the type of energy used for production (energy 1–5), the type of sugar used for production (sugar 1–3), production location (country), and whether transportation of inputs was considered (transportation).

**Table 2. Model scenarios**

| Scenario | Baseline input amounts used | Sugar source | Energy source |
|---|---|---|---|
| Baseline (Low-end) | Low | Beet | Natural gas |
| Baseline (high-end) | High | Beet | Natural gas |
| Energy 1 | Low | Beet | Natural gas w/ extraction |
| Energy 2a | Low | Beet | Nuclear |
| Energy 2b | High | Beet | Nuclear |
| Energy 3 | Low | Beet | Nuclear w/ extraction |
| Energy 4a | Low | Beet | Coal |

| Scenario | Baseline input amounts used | Sugar source | Energy source |
|---|---|---|---|
| Energy 4b | High | Beet | Coal |
| Energy 5 | Low | Beet | Coal w/ extraction |
| Sugar 1a | Low | Cane (Brazil) | Natural gas |
| Sugar 1b | High | Cane (Brazil) | Natural gas |
| Sugar 2a | Low | Cane (Avg. World) | Natural gas |
| Sugar 2b | High | Cane (Avg. World) | Natural gas |
| Sugar 3a | Low | Glucose | Natural gas |
| Sugar 3b | High | Glucose | Natural gas |
| Country 1a (India) | Low | Cane | Coal |
| Country 1b (India) | High | Cane | Coal |
| Country 2 (America) | Low | Cane | Coal |
| Transportation of inputs (Cross-Country) | Low | Beet | Natural Gas |

*Note*: Rows highlighted in blue represent high-end scenarios, rows in white are low-end scenarios.

### *Literature Review – Traditional Milk Production LCAs*

To create a comparative analysis of the environmental impact of cultured protein and the environmental impact of traditional milk, a literature review was conducted to understand the range of carbon emissions for traditional milk production. We did not include LCAs for other "milks" (e.g., soy, oat, almond, etc.) in our literature review because cultured casein is identical to the casein found in traditional milk, so this is its most direct comparator. Key search terms, including but not limited to, "LCA of milk," "LCA of dairy," "LCA of milk in [target country]," "environmental impact of milk production," were used in the Duke University online library search function. Other publicly available search engines such as Google Scholar were also used, but the results often fell outside of the scope of this study, so the majority of papers were found and accessed through the Duke University online library. Within the target countries, India and Ethiopia had the most relevant results; there were no papers that discussed the impact of milk production in Senegal or Vietnam. For all of the papers, the functional unit of the LCA was a kilogram of milk, or a kilogram of fat-and-protein corrected milk (FPCM). In order to compare the results of the milk LCAs with the results of the cultured protein LCA, the environmental impact of the milk LCAs had to be converted to impact per kilogram of protein. Assuming 33 grams of protein per kilogram of milk, below is the calculation used to convert to global warming potential per kilogram of protein.

$$\frac{kg\ of\ CO_2\ eq.per\ liter\ of\ milk}{33\ grams\ of\ protein} = \frac{X\ kg\ of\ CO_2\ eq.per\ liter\ of\ milk}{1000\ grams\ of\ protein}$$

### *Cultured Milk Production Carbon Offsets Calculation*

To understand the benefits that a cultured protein manufacturer might receive from selling carbon credits, we created a hypothetical food-aid program that is switching a protein source from animal-sourced to cultured proteins. To calculate the credits, we need to understand the difference in net GHG emissions between a project baseline scenario (business as usual using animal source proteins) and the cultured protein scenario (with the cultured protein project in place).

In order to create the cultured protein scenario, we had to estimate the following values:

#### *The Amount of Milk Protein That Could Be Replaced in One Year for a Food Aid Organization (Protein Replaced)*

Based on existing reports, we are assuming that 5% of total annual food aid by weight from a program such as USAID's Food for Peace represents milk protein (obtained from skim milk powder) (Herrick et al. 2019). This represents 156,233,450 kg milk protein annually that could be replaced by cultured milk protein. For our scenario, we will assume that Food for Peace might do a pilot project replacing 5% of that total milk protein with cultured milk protein, representing 7,811,672 kg milk protein replacement.

#### *The Range of Prices You Might Receive for a Credit (Price)*

We found a variety of selling prices for carbon credits on the voluntary market, ranging from an average price of $3.10 as reported by Ecosystem Marketplace to a range of $10–$28 in the Gold Standard marketplace (Donofrio et al. 2019; Offset Your Emissions | The Gold Standard, n.d.). We therefore chose to analyze our scenario selling credits at $3, $10, and $28 per credit.

We then calculated the number and value of credits possibly produced by our hypothetical project. This is based on the differential in GHG emissions between our LCA scenarios for cultured casein production and the values obtained from the literature review on emissions generated from traditional milk protein production. We used four different LCA scenarios to show what offset calculations would look like for the range of results from the low and high-end scenarios described.

## RESULTS

### *LCA Results for Cultured Proteins*

The scenarios described below depict the combinations of energy, sugar, efficiency, and transportation to determine the climate change, water consumption, and land use impacts of producing 1 kg of casein for all our different scenarios described in Table 2. Climate change effects are reported in terms of Global Warming Potential (GWP), which measures the amount of energy one ton of a greenhouse gas (e.g., methane) will absorb in the atmosphere, relative to the amount of energy a ton of $CO_2$ emitted will absorb (U.S. EPA 2016).

For the low-end input levels, scenarios show that to produce 1 kg of cultured casein, the process will emit 0.89–37.21 kg of $CO_2$ eq., use 2.05–8.64 $m^3$ water, and require a land footprint of 0.0096–1.07 $m^2a$ crop eq. For the high-end input levels, scenarios show that to produce 1 kg of cultured casein the process will emit 40.05–146.5 kg of $CO_2$ eq., use 38.33–313.56 $m^3$ water, and require a land footprint of 0.46–50.94 $m^2a$ crop eq. To reiterate, we expect that actual cultured protein production at scale will more closely resemble a low-end input scenario rather than the high-end. The most resource intensive low-end scenarios emit 4x less GHG, 36x less water, and 48x less land than the most resource intensive high-end scenarios. Clearly, the higher resource inputs used for the high-end baseline greatly affect the environmental impact of producing cultured proteins.

### Table 3. Results from each of the LCA scenarios

| | | | Inputs | | Per 1 kg casein produced | | |
|---|---|---|---|---|---|---|---|
| **Scenario** | **Baseline Input** | **Energy Source** | **Sugar Source** | **Culture Media** | **GWP (Climate Impact)** | **Water Consumption** | **Land Use** |
| | | | | **Energy Analysis** | | | |
| Baseline (low-end) | n/a | Natural Gas | Beet | None | 9.66 kg of $CO_2$ eq. | 3.17 $m^3$ | .0096 $m^2a$ crop eq. |
| Baseline (high-end) | n/a | Natural Gas | Beet | Cyano-bacteria | 64.09 kg of $CO_2$ eq. | 101.33 $m^3$ | 0.46 $m^2a$ crop eq. |
| Energy Scenario 1 | Low | Natural Gas w/ Extraction | Beet | None | 11.27 kg of $CO_2$ eq. | 3.76 $m^3$ | 0.0104 $m^2a$ crop eq. |
| Energy Scenario 2a | Low | Nuclear Power | Beet | None | 0.89 kg of $CO_2$ eq. | 5.64 $m^3$ | 0.01 $m^2a$ crop eq. |
| Energy Scenario 2b | High | Nuclear | Beet | Cyano-bacteria | 40.05 kg of $CO_2$ eq. | 108.09 $m^3$ | 0.46 $m^2a$ crop eq. |
| Energy Scenario 3 | Low | Nuclear Power w/ Extraction | Beet | None | 1.2 kg of $CO_2$ eq. | 8.64 $m^3$ | 0.013 $m^2a$ crop eq. |
| Energy Scenario 4a | Low | Coal | Beet | None | 22.26 kg of $CO_2$ eq. | 5.47 $m^3$ | 0.167 $m^2a$ crop eq. |
| Energy Scenario 4b | High | Coal | Beet | Cyano-bacteria | 98.59 kg of $CO_2$ eq. | 107.62 $m^3$ | .888 $m^2a$ crop eq. |
| Energy Scenario 5 | Low | Coal w/ Extraction | Beet | None | 26.42 kg of $CO_2$ eq. | 7.81 $m^3$ | 0.321 $m^2a$ crop eq. |
| | | | | **Sugar Analysis** | | | |
| Sugar Scenario 1a | Low | Natural Gas | Cane (Brazil) | None | 9.8 kg of $CO_2$ eq. | 2.05 $m^3$ | 0.902 $m^2a$ crop eq. |

| | | | Inputs | | Per 1 kg casein produced | | |
|---|---|---|---|---|---|---|---|
| **Scenario** | **Baseline Input** | **Energy Source** | **Sugar Source** | **Culture Media** | **GWP (Climate Impact)** | **Water Consumption** | **Land Use** |
| Sugar Scenario 1b | High | Natural Gas | Cane (Brazil) | Cyano-bacteria | 71.38 kg of $CO_2$ eq. | 38.33 $m^3$ | 50.47 $m^2a$ crop eq. |
| Sugar Scenario 2a | | Natural Gas | Cane (Avg. World) | None | 10.03 kg of $CO_2$ eq. | 2.45 $m^3$ | 0.122 $m^2a$ crop eq. |
| Sugar Scenario 2b | High | Natural Gas | Cane (Avg. World) | Cyano-bacteria | 84.18 kg of $CO_2$ eq. | 60.35 $m^3$ | 6.79 $m^2a$ crop eq. |
| Sugar Scenario 3a | Low | Natural Gas | Glucose | None | 10.40 kg of $CO_2$ eq. | 6.96 $m^3$ | 0.013 $m^2a$ crop eq. |
| Sugar Scenario 3b | High | Natural Gas | Glucose | Cyano-bacteria | 105.27 kg of $CO_2$ eq. | 313.57 $m^3$ | 0.65 $m^2a$ crop eq. |
| | | | | **Country Analysis** | | | |
| Country Scenario 1a | Low | Coal (India) | Cane | None | 37.21 kg of $CO_2$ eq. | 6.01 $m^3$ | 1.07 $m^2a$ crop eq. |
| Country Scenario 1b | High | Coal (India) | Cane | Cyano-bacteria | 146.50 kg of $CO_2$ eq. | 48.19 $m^3$ | 50.94 $m^2a$ crop eq. |
| Country Scenario 2 | Low | Coal (America) | Cane | None | 22.39 kg of $CO_2$ eq. | 4.35 $m^3$ | 1.06 $m^2a$ crop eq. |
| | | | | **Transportation Analysis** | | | |
| Cross-Country Transportation | Low | Natural Gas | Beet | | 10.72 kg of $CO_2$ eq. | 4.05 $m^3$ | 0.036 $m^2a$ crop eq. |

*Note*: Rows highlighted in blue represent high-end scenarios, rows in white are low-end scenarios.

Of the various fuel sources, nuclear power produces the least amount of emissions, followed by natural gas and coal energy. However, nuclear power is not widely used in the U.S., so it is likely the production of cultured protein will primarily use either natural gas or coal energy for the time being. There was not much variance in the GWP of the three different sugar sources, except it should be noted that glucose uses considerably more water. With that in mind, changing the sugar source in cultured protein production should not create a large difference in the environmental impact. Alternatively, the production country can vastly change the environmental impact of cultured protein production. Given existing efficiencies in transportation, transporting goods from one end of the country to the other, in this case from the southeastern U.S. to the western U.S., produces only a small change in the climate change impact. It is not a significant contributor. Within these results there are tradeoffs between the scenarios. For example, nuclear power produces the least GWP but uses considerably more water. Alternatively, natural gas has a greater GWP with lower water consumption.

### *LCA Results – Traditional Milk Protein*

The LCAs obtained on traditional milk protein are all from 2010 or later and range from small to large producers and from global averages to specific country estimates (Table 4). While the LCAs listed in Table 4 are not comprehensive of all the various traditional milk production scenarios, it provides a range of the environmental impact of milk production. This can be used as a preliminary guideline for comparative purposes to identify the differences in environmental impact for cultured protein production and traditional milk production, and how these differences can be translated into carbon credits.

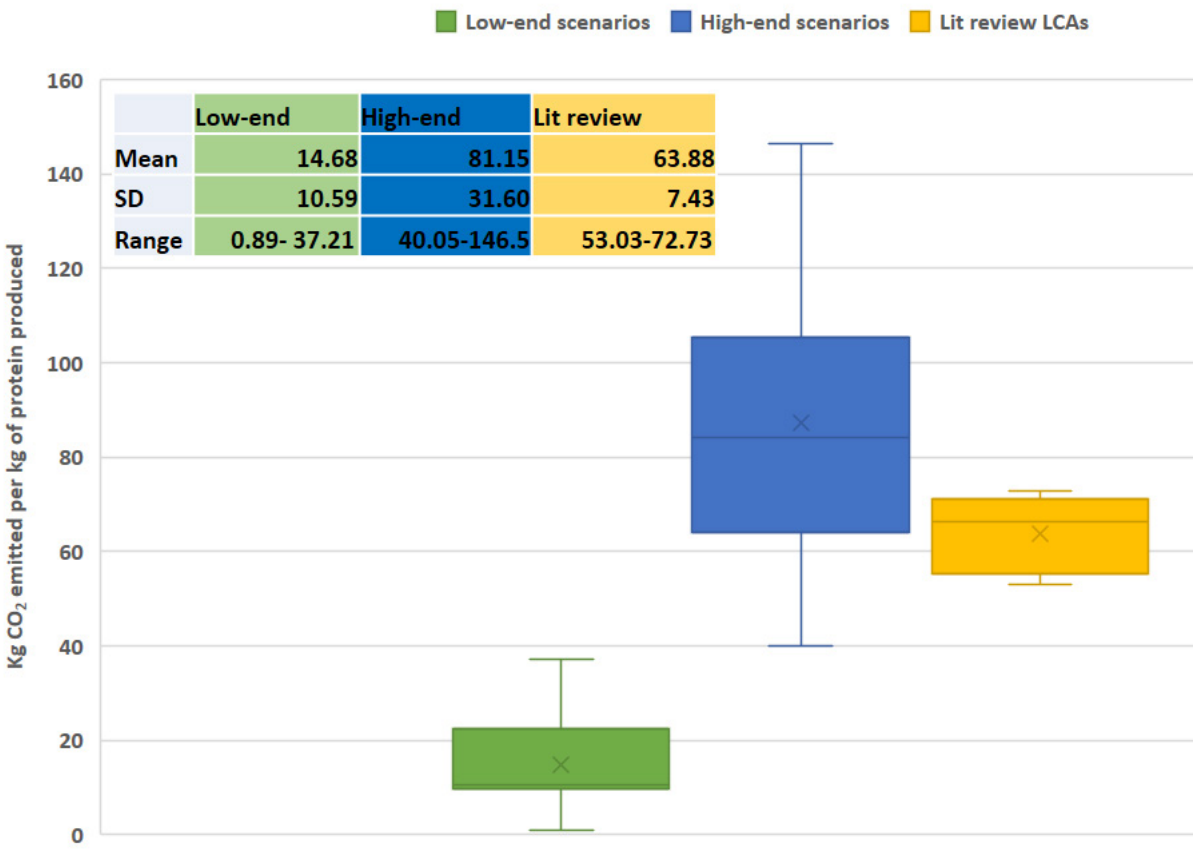
**Table 4. Values obtained from the literature describing the GHG emissions from traditional milk production**

| Title | Year | Country | Operation Scale | System Boundaries | Functional Unit | GWP |
|---|---|---|---|---|---|---|
| Greenhouse Gas Emissions from the Dairy Sector: A Life Cycle Assessment | 2010 | Global Average | Average of global operations | Cradle to Farm Gate | Kg of fat-and-protein-corrected milk (FPCM) | 2.4 kg of $CO_2$ eq. |
| Greenhouse Gas Emissions from the Dairy Sector: A Life Cycle Assessment | 2010 | Regional Average – East Asia | Average of regional systems | Cradle to Farm Gate | Kg of fat-and-protein-corrected milk (FPCM) | 1.9 kg of $CO_2$ eq. |
| Carbon Footprint of Milk Production Under Smallholder Dairying in Anand District of Western India: A cradle-to-farm gate life cycle assessment | 2016 | India | Smallholder dairy farms | Cradle to Farm Gate | Kg of fat-and-protein-corrected milk (FPCM) | 2.3 kg of $CO_2$ eq. |
| Environmental Impact of Milk Production Across an Intensification Gradient in Ethiopia | 2017 | Ethiopia | Large, urban, peri-urban, and rural | Cattle-keeping to Farm Gate | Kg of milk | 1.75 for large; 2.25 for urban and peri-urban, 2.2 kg of $CO_2$ eq. for rural |
| Variation in the Carbon Footprint of Milk Production on Smallholder Dairy Farms in Central Kenya | 2020 | Kenya | Smallholder Dairy Farms | Cradle to Farm Gate | Kg of fat-and-protein-corrected milk (FPCM) | 2.19 – 3.13 kg of $CO_2$ eq. |

### *Comparison of Cultured and Traditional Milk Protein*

Figure 2 depicts the range of GWP for the modeled scenarios, as well as the results determined through the LCA literature review, and shows that the more likely/representative low-end modeled scenarios produce less of an environmental impact in terms of climate change. Table 5 shows the GWP values from Table 4 converted to a standardized unit of $CO_2$ eq. per kilogram of protein in order to compare values from milk production LCAs found in the literature to our results from the modeling scenarios. One kilogram of fat and protein corrected milk (FPCM) and a kilogram of milk were considered the same when standardizing for protein because a kilogram of FPCM contains about 3.3% protein, which is the conversation factor (33 g of protein) we used.

**Figure 2. Comparison of GWP between our cultured proteins LCA scenarios and LCA results from other studies examining emissions from traditional milk protein production**




| | Low-end | High-end | Lit review |
|---|---|---|---|
| Mean | 14.68 | 81.15 | 63.88 |
| SD | 10.59 | 31.60 | 7.43 |
| Range | 0.89- 37.21 | 40.05-146.5 | 53.03-72.73 |

**Table 5. Direct comparison between our LCA results for cultured proteins and literature values for production of traditional milk**

| | Scenario | GWP (per kg of protein) |
|---|---|---|
| Cultured protein LCA scenario results | Model – Low-end Baseline (Natural Gas and Beet Sugar) | 9.66 kg of $CO_2$ eq. |
| | Model – High-end Baseline (Natural gas and beet sugar, high end baseline inputs) | 64.09 kg of $CO_2$ eq. |
| | Model – Energy Scenario 2 (Nuclear Power and Beet Sugar, low-end baseline inputs) | 0.89 kg of $CO_2$ eq. |
| | Model – Energy Scenario 2b (Nuclear and beet sugar, high-end baseline inputs | 40.05 kg of $CO_2$ eq. |
| | Model – Country Scenario 1a (Indian coal, low-end baseline inputs) | 37.21 kg of $CO_2$ eq. |
| | Model—Country scenario 1b (Indian coal, high-end baseline inputs) | 146.5 kg of $CO_2$ eq. |
| Traditional milk production literature review LCA results | Global Average | 72.73 kg of $CO_2$ eq. |
| | East Asia Regional Average | 57.57 kg of $CO_2$ eq. |
| | Smallholder Dairy Farm – India | 69.70 kg of $CO_2$ eq. |
| | Smallholder Dairy Farm – Ethiopia | 53.03 – 68.18 kg of $CO_2$ eq. |
| | Smallholder Dairy Farm – Kenya | 66.36 – 94.85 kg of $CO_2$ eq. |

*Note*: For our LCA results, rows highlighted in blue represent high-end scenarios, rows in white are low-end scenarios.

## *Carbon Credit Results*

We estimate that the differential in GHG emissions between production of cultured milk protein and milk protein obtained from skim milk powder (what cultured proteins would be replacing) ranges from 1.26–76.68 kg $CO_2$e/kg milk protein. This was calculated using the following information.

We selected four scenarios from those listed in Table 3: two low-end scenarios and two high-end scenarios to represent a range of GHG emissions from cultured protein production. The two low end scenarios were (Scenarios):

- $Scenario_1$ = 0.89 kg $CO_2$e/kg protein produced (corresponding to energy scenario 2a, the nuclear power/beet sugar low-end scenario, the lowest emission scenario overall)
- $Scenario_2$ = 37.21 kg $CO_2$e/kg protein produced (corresponding to country scenario 1a, the Indian production low-end scenario, the highest emission low-end scenario)

The two high-end scenarios were:

- $Scenario_3$ = 40.05 kg $CO_2$e/kg protein produced (corresponding to energy scenario 2b, the nuclear power/beet sugar high-end scenario, the lowest emission high-end scenario)

- *Scenario*$_4$ = 64.09 kg $CO_2$e/kg protein produced (corresponding to the high-end baseline scenario)

Scenario 3 and 4 are the only two high-end scenarios with emissions significantly lower than that of traditional powdered milk production. There would be no opportunity for carbon credits if emissions for cultured protein production were higher than that of traditional powdered milk production.

The global average emissions for cradle to farm gate production of milk according to the FAO is 2.4 kg$CO_2$e/kg FPCM, which translates to 72.7 kg $CO_2$e/kg milk protein (Food and Agriculture Organization of the United Nations 2010). This was selected to be a conservative estimate that would be broadly applicable. Because we are comparing cultured casein to powdered milk protein, we needed to add emissions for the production of milk powder from milk, which we estimate as 4.88 kg $CO_2$e/kg milk protein.[1] Therefore, the total emissions from production of milk powder are 77.58 kg $CO_2$e/kg powdered milk protein produced.[2]

77.58 kg $CO_2$/kg powdered milk protein produced – *Scenario*$_{1-4}$ kg $CO_2$e/kg cultured milk protein = *Differential*$_{1-4}$.

The four Differentials calculated using LCA Scenarios 1–4 are:

- *Differential*$_1$ = 76.69 kg $CO_2$e/kg protein
- *Differential*$_2$ = 40.37 kg $CO_2$e/kg protein
- *Differential*$_3$ = 37.53 kg $CO_2$e/kg protein
- *Differential*$_4$ = 13.49 kg $CO_2$e/kg protein

Leakage estimates (*Leakage*) are incorporated into the calculation of carbon credits to account for the fact that efforts to reduce emissions may in fact result in some emissions reductions being counteracted by increased emissions in some other sector or location[3] (Jenkins et al. 2009; Parker and Blodgett 2008). We chose to use a *Leakage* rate of 20%, which is the rate used in the 2015 California Offset Protocol for U.S. Forest Projects[4] (California Environmental Protection Agency Air Resources Board 2015). There is no basis in the literature for a different leakage rate related to cultured milk protein use.

Using 7,811,672 kg milk protein as the *Protein Replaced* value,[5] it is then possible to use the following equation to calculate the number of credits (*Credits*) a project could generate:

*Protein Replaced* (kg milk protein) * *Differential* (kg$CO_2$e/kg milk protein)$_{1-4}$ * 1 tonne/1000 kg * (1-*Leakage*) = *Credits*$_{1-4}$

1. Krokida et al. (2016) report emissions of 1.27 kg $CO_2$e/kg milk powder, if you assume there is 260 g protein in 1 kg milk powder, this translates to 4.88 kg$CO_2$e/kg powdered milk protein (FoodData Central, n.d.).
2. 72.7 kg $CO_2$e/kg milk protein produced + 4.88 kg $CO_2$e/kg powdered milk protein produced = 77.58 kg $CO_2$e/ kg powdered milk protein produced.
3. An example of leakage in a cultured protein project could be an instance where some proportion of traditional milk powder not used in food-aid packages being transitioned to other uses, rather than being fully replaced by a cultured protein alternative.
4. This leakage rate was selected based on conversations with carbon credit experts who predicted that theoretical cultured protein carbon credits would likely have a high leakage rate, similar to that of forest projects.
5. The calculation of this *Protein Replaced* value is described in the methods.

Using Price values of $3, $10, and $28,[6] it is possible to calculate the range of values ($Value_{1-12}$) for those credits:

$$Price_{1-3} * Credits_{1-4} = Value_{1-12}$$

The hypothetical food-aid cultured protein project generated between 84,304 and 479,262 carbon credits, which are valued between $253,000 and $13.4 million (Table 6). The results range depending on the GHG emissions *Differential* and credit sale *Price* used.

### Table 6. Potential value of carbon credits generated from a hypothetical cultured protein project

| | | | Value of Credits | | |
|---|---|---|---|---|---|
| Low or high-end scenario? | | ***# Credits* generated** | **At $3/ credit** | **At $10/ credit** | **At $28/ credit** |
| **Low** | Nuclear power/beet sugar production scenario (using *Differential*$_1$) | 479,262 | $1.4 million | $4.8 million | $13.4 million |
| | Indian CP production scenario (using *Differential*$_2$) | 252,286 | $757,000 | $2.5 million | $7.1 million |
| **High** | Nuclear power/beet sugar production scenario (using *Differential*$_3$) | 234,538 | $703,613 | $2.3 million | $6.6 million |
| | Baseline high-end production scenario (using *Differential*$_4$) | 84,304 | $253,000 | $843,000 | $2.4 million |

*Note*: Rows highlighted in blue represent credit estimations created using GHG differentials from high-end scenarios, rows in white are credit estimations created using low-end scenarios.

## DISCUSSION

If cultured milk protein production is more similar to the low-end LCA results as we expect it would be, the environmental impacts of cultured casein will be significantly less than those for proteins from traditional milk. Even the most resource intensive low-end scenario, with production in India using coal as the primary energy source, resulted in lower emissions per kilogram of cultured casein than the production of traditional milk protein. However, if cultured milk protein production is more similar to the high-end scenarios with high energy and sugar input requirements, cultured protein production could result in emissions equal to or even greater than that of traditional milk production. As discussed earlier, we believe that the true cultured protein production process likely falls somewhere between our low and high-end scenarios in terms of environmental impact and is likely more similar to that of a low-end scenario. Further research that incorporates more specifics on the actual chemical processes and

6. Explanation for these *Price* values described in the methods.

inputs of cultured casein production will be able to provide insight into where exactly on that spectrum these products fall.

Energy source and efficiency are large determinants of the environmental impact of cultured protein production, and these inputs should be given greater consideration when analyzing the process. Sugar input requirements are the most important consideration when it comes to land and water use.

### *Energy*

Not surprisingly, energy was generally the largest contributor to GWP. Concentrating production in regions that use natural gas or nuclear power as the main fuel source is key when considering future production scenarios. The only scenarios in which electricity production was not the largest contributor to GWP were those with high sugar inputs (60 kg of sugar). Energy accounted for about 90% of the emissions and 45% of the water use in most cases. Nuclear power production is more water intensive, thus the scenarios with nuclear power as the energy input have larger contributions to water consumption (about 69%). However, this is not the case when there are high sugar inputs, and those contributions are discussed in the Sugar section below. In contrast, traditional milk LCAs indicate that methane production through enteric fermentation by cows is the primary source of GHG emissions related to animal source milk production (FAO 2010; Garg et al. 2016; Woldegebriel et al. 2017; Wilkes et al. 2020).

Three energy sources were compared, based on the common fuel sources in both the current production region (western U.S.) and target production countries (Ethiopia, India, Senegal, and Vietnam), as well as their ability to provide variance in the range of environmental impact. The three energy sources were natural gas, coal, and nuclear power. Production with coal as the primary fuel source resulted in a $CO_2$ equivalent that was more than double the next closest energy source. A fourth energy source, hydropower, was considered but ultimately not analyzed because in the regions where hydropower is prevalent, coal is more widely used. In addition, three more scenarios were modeled that included the environmental impact of extracting the raw fuel source (i.e., natural gas, hard coal, uranium pellets). As Table 3 above shows, if extraction was included in the model, there was a 15–35% increase in GWP, and a 15–50% increase in water use, compared to the non-extractive scenario. Extraction is the most intensive step of the process. In order to allow for greater examination of the other phases of the process and to be consistent with the other LCAs found through the literature review, extraction was not included in the final models used to compare environmental impact of cultured protein and traditional milk protein.

### *Sugar*

Selecting sugar inputs followed a similar process as the fuel sources. Three sugars were identified—beet, sugar cane, and corn syrup (glucose)—because of their availability in the current production and target production regions. Glucose is not commonly used currently for cultured protein production but is a plausible alternative for future production. In the ecoinvent database, sugar cane data was only available for production in Brazil, and an average of world production data, however, it is likely that India would use sugar cane processed within the country, which may change environmental impact slightly. Generally, the GWP did not vary much between the different sugar inputs, but there was a notable difference in the water consumption and land use. However, for the scenarios with high baseline sugar inputs (60

kg sugar input per 1 kg protein output) the contributions of sugar production to GWP were significant and in some cases outweighed the impacts caused by electricity use. For sugar inputs, water consumption and land use impacts can be significant and varies by source. The sugar source is an important consideration because sugarcane harvesting and processing is less water intensive than beet harvesting and processing. In the high-end scenarios, water and land use were up to 150 and 6,000 times higher, respectively, based on the greater sugar inputs that we assumed for these more resource intensive scenarios.

### *Transport*

Transporting input resources (sugar) results in a very small change in the climate change impact, likely because the inputs for cultured protein production are transported in mass quantities, thus the impact per kilogram of input is minimal.

### *Low- and High-End Inputs*

As stated earlier, our low- and high-end input assumptions are used to represent the uncertainty surrounding the cultured protein production process. Low-end scenarios assume a relatively simple chemical process with minimal energy and sugar inputs required, while high-end scenarios assume that the chemical complexity of producing a protein from scratch requires much more energy, sugar, and an additional culture medium. We expect that the true process, once brought to scale and full efficiency, will more closely resemble our low-end estimates based on conversations with industry experts and GHG calculations for similar products. If that is the case, cultured proteins have a less intensive environmental footprint than traditional milk, however, if inputs required mirror those from our high-end scenario, cultured proteins could have higher impacts on GHG emissions than traditional milk. Further research with more detailed specifications on the cultured protein production process will clarify which production scenario is more likely.

### *Carbon Credits*

In the context of our hypothetical cultured protein food-aid project, it appears that cultured protein-based carbon credits might generate significant revenue. Sources note that buyers prefer to purchase credits that can show additional co-benefits beyond emissions reductions, and are sometimes willing to pay a premium if those benefits can be proven (Donofrio et al. 2019). Cultured protein projects would likely be able to report on other positive outcomes—nutritional benefits, reduced air pollution from cows and associated health impacts, and benefits to animal welfare. Therefore, these projects could possibly fetch a higher price than the average, indicating they might be able to generate credits sold at the $10–28 range, rather than the $3 average. However, it is important to note that voluntary markets often have an excess of credits (Hamrick and Gallant 2017), and a large project such as the one we hypothesize might in turn be forced to sell credits in the lower price range because they would need to be competitively priced. One carbon market expert we spoke to stated it was unlikely that credits for a project such as this would sell higher than the global average of $3/credit. It should also be noted that the cost of cultured casein production to that of skim milk powder would determine how much relative benefit can really be gained from carbon offset finance.

There are additional uncertainties that should be considered in the context of our carbon credit analysis. There is a possibility that the number of carbon credits generated by a cultured protein project like the one we hypothesized would be lessened due to higher leakage rates or automatic credit reductions linked to uncertainty that is inherent to some verification schemes. Because we are not working with a particular credit verifier, marketplace, or protocol these possible sources of credit reductions are uncertain at this time. There is significant uncertainty about what a protocol for cultured proteins would look like. Would it be based on an LCA and assume that there is perfect substitution where one unit of cultured protein replaces one unit of traditional protein in the marketplace? Or would a market analysis be required to determine if the new product is simply increasing overall protein uptake, rather than replacing traditional animal source proteins? Additionally, there can be significant costs associated with establishing a protocol, and depending on the protocol there can be additional transaction costs for each project to get carbon credits verified for sale on a market (Pearson et al. 2014; Phan et al. 2017). Each individual project would need to determine whether the number of potential credits and their associated value would adequately offset those transaction costs to make production of credits worthwhile. Another consideration is that the process of getting credits verified takes time; for some credit types it can be up to 2.5 years (Hamrick and Gallant 2017). Projects would need to also consider that generation of carbon credits does not automatically translate into revenue generation. There is no guarantee that credits on the market will sell; in 2016 voluntary carbon offset organizations produced more offsets than they sold (Hamrick and Gallant 2017).

### *Comparison to Similar Products*

The GWP for production of 1 kg of cultured casein presented in our scenarios ranges from 0.89–37.21 kg of $CO_2$ eq. for low-end estimates and 40.05–146.5 kg of $CO_2$ eq. for high-end estimates. LCAs identified for similarly produced products (citric acid, cultured meat, microbe-produced enzymes) indicate a GWP ranging from 1–25 kg of $CO_2$ eq. per kg product (Table S1). We were recently given access to unpublished results of a preliminary analysis to estimate environmental impact of fermentation-produced protein by the large-scale enzyme production company Novozymes. Novozymes has made a visionary estimate of the environmental impact of producing 1 kg of protein for human consumption through fermentation. The assessment is based on the company's experience from enzyme manufacturing for industrial purposes (Jegannathan and Nielsen 2013) and life cycle assessment in a cradle-to-gate perspective has been used as analytical tool (Nielsen et al. 2007). The final protein product is assumed to be delivered in a concentrated spray-dried powder format. Novozymes estimates 4.3 kg $CO_2$ eq. per kg of protein produced. This value is not specific to milk protein, but it does incorporate more detail on the estimated protein production process than we were able to incorporate. This combination of evidence indicates to us that cultured protein production, once brought to scale and high efficiency, may very well fall within that 1–25 kg of $CO_2$ eq. per kg protein range. However, we cannot completely discount higher-end scenarios at this stage because of the uncertainty surrounding the specific production process, location, and energy source. Our scenarios indicate that primary energy source and the amount and type of sugar required for the process are likely "hotspots" in the production process. As research and development on these products progresses, any effort to keep energy and sugar inputs low will help keep the environmental footprint lower. Selecting a production location that uses an energy mix primarily made up of lower emissions sources would also keep the GWP potential down.

## FUTURE STEPS

Being such a novel technology, established data were not available to prepare a generic LCA for cultured protein production. Data from citric acid production, Italian lager beer, enzyme production, and cultured meat production provide an estimate to base our understanding of the differential in environmental footprints between animal source and cultured proteins and whether there is enough of a difference in GHG emissions to potentially pursue a carbon offset project. More specific and accurate data are needed to concretely determine the difference in environmental impact. In the scenarios of production in target countries, very little is known about the conditions (energy source, sugar source, efficiency, etc.) for the use of this production technology. Estimating this required a series of assumptions based on possible country conditions. More clarity and understanding of the production process will decrease uncertainty and assumptions, in turn creating greater confidence in the results.

Some of the LCAs for traditional milk that we pulled from the literature analyzed industrial, large-scale milk production, compared to the current state of cultured protein production, which is at a small scale. Learning how scaling would affect the process and efficiency of cultured protein production could help create a more comparable scenario for industrial milk production.

The possible uses of cultured protein are vast, ranging from use as a protein additive in food products, food aid, or as a vegan alternative to animal-sourced milk. The comparative LCA would be different for all of these uses because the end product is different, thus requiring a different set of inputs and comparison to a different product. For this project, the focus was on food aid, to supplement populations with malnourished diets that may not have access to traditional milk. Further understanding of how cultured protein would be used as food aid could better inform the process and eliminate some assumptions that are made or provide a better comparison scenario.

The establishment of carbon credits for cultured proteins requires significant further effort. Standard methods would be needed to estimated carbon benefits of cultured products, with well-established estimates for leakage and uncertainty and clear verification methods. Additional work would also be needed to set bounds around what would qualify as a carbon project for cultured protein that would clearly be additional (replacing traditional forms of milk). It would also be interesting to look into the establishment of additional credits based on potential afforestation of land previously used for cow pasture and livestock feed production. If the cultured milk protein market truly takes off and decreases the amount of land used to raise cows, there is potential for increased credit generation based on carbon sequestration by new trees growing on old pastureland. However, cultured protein manufacturers would likely not be generating this type of credit. Even without additional credit value, we can say that preliminary results of this study indicate that future efforts to pursue carbon credits based on cultured protein projects is a worthwhile endeavor because of the potential income.

## CONCLUSION

Though this was a preliminary LCA limited by data availability and an incomplete understanding of the developing cultured protein production process, there is enough of an expected difference in the environmental impact of cultured protein versus traditional milk protein that pursuing further research into carbon credits is justified. The estimated differences in environmental impact suggest potential for lucrative carbon credit generation, if it could be proven that cultured

protein replaces traditional milk protein. Based on rough calculations and a very conservative approach, a food-aid project that replaces traditional milk protein with cultured milk protein could result in income ranging from $253,000 to $13.4 million through carbon credit sales.

## REFERENCES


Alexandratos, N., and J. Bruinsma. 2012. World Agriculture towards 2030/2050: The 2012 Revision. ESA Working Paper No. 12-03.

Becker, M.-Y., N. Kohlheb, S. Hunger, S. Eschrich, R. Müller, and A. Aurich, A. 2020. "Early-stage Sustainability Assessment of Biotechnological Processes: A Case Study of Citric Acid Production." *Engineering in Life Sciences* 20(3–4): 90–103. https://doi.org/10.1002/elsc.201800198.

Beyond Meat—Products. n.d. Beyond Meat - Go Beyond®. Retrieved June 28, 2020, from https://www.beyondmeat.com/products/.

California Environmental Protection Agency Air Resources Board. 2015. Compliance Offset Protocol: U.S. Forest Projects. https://ww3.arb.ca.gov/cc/capandtrade/protocols/usforest/forestprotocol2015.pdf.

Cordella, M., A. Tugnoli, G. Spadoni, F. Santarelli, and T. Zangrando. 2008. "LCA of an Italian Lager Beer." *The International Journal of Life Cycle Assessment* 13(2): 133–139. https://doi.org/10.1065/lca2007.02.306.

Davoodi, S. H., R. Shahbazi, S. Esmaeili, S. Sohrabvandi, A. Mortazavian, S. Jazayeri, and A. Taslimi, A. 2016. "Health-Related Aspects of Milk Proteins." *Iranian Journal of Pharmaceutical Research: IJPR* 15(3): 573–591.

Donofrio, S., P. Maguire, W. Merry, and. S. Zwick. 2019. Financing Emissions Reductions for the Future: State of the Voluntary Carbon Markets 2019. Forest Trends' Ecosystem Marketplace.

Feijoo, S., S. González-García, J.M. Lema, and M.T. Moreira. 2017. "Life Cycle Assessment of β-Galactosidase Enzyme Production." *Journal of Cleaner Production* 165: 204–212.

Food and Agriculture Organization of the United Nations. 2010. Greenhouse Gas Emissions from the Dairy Sector: A Life Cycle Assessment.

FoodData Central. n.d. Milk powder protein data. Retrieved June 22, 2020, from https://fdc.nal.usda.gov/fdc-app.html#/?query=ndbNumber:1175

Garg, M.R., B.T. Phondba, P.L. Sherasia, H.P., and Makkar. 2016. "Carbon Footprint of Milk Production under Smallholder Dairying in Anand District of Western India: A Cradle-to-Farm Gate Life Cycle Assessment." *Animal Production Science* 56(3): 423–436.

Hamrick, K., and M. Gallant. 2017. Unlocking Potential: State of the Voluntary Carbon Markets 2017. Ecosystem Marketplace. https://forest-trends.org/wp-content/uploads/2017/07/doc_5591.pdf.

Haug, A., A.T. Høstmark, and O.M. Harstad. 2007. "Bovine Milk in Human Nutrition—A Review." *Lipids in Health and Disease* 6: 25. https://doi.org/10.1186/1476-511X-6-25.

Herrick, T., S. Gannon, K. Kreis, S. Zobrist, M. Parker, C. Harner-Jay, et al. 2019. Market Analysis for Cultured Proteins in Low- and Lower-Middle Income Countries. PATH. https://path.azureedge.net/media/documents/PATH_Cultured_Proteins_Market_Landscape_and_Analysis_FINAL_Dec2_2019.pdf.

Herrick, T., N. Perez, D. Shindell, M. Parker, C. Ringler, J. Goldstein, and K. Kreis. 2020. "How Now Brown Cow?: Cultured Proteins for Milk: A Solution for Human and Planetary Health?" Manuscript submitted for publication.

Huijbregts, M.A.J., Z.J.N. Steinmann, P.M.F. Elshout, G. Stam, F. Verones, M.D.M. Vieira, et al. 2016. "ReCiPe 2016 v1.1: A Harmonized Life Cycle Impact Assessment Method at Midpoint and Endpoint Level—Report I: Characterization." *The International Journal of Life Cycle Assessment* 22: 138–147.

Jegannathan, K. R., and P. H. Nielsen. 2013. "Environmental Assessment of Enzyme Use in Industrial Production–A Literature Review." *Journal of Cleaner Production* 42: 228–240.

Jenkins, W.A., L.P. Olander, and B.C. Murray. 2009. "Addressing Leakage in a Greenhouse Gas Mitigation Offsets Program for Forestry and Agriculture." NI PB 09-03. Durham, NC: Duke University, 11.

Kim, S., C. Jiménez-González, and B.E. Dale. 2009. "Enzymes for Pharmaceutical Applications—A Cradle-to-Gate Life Cycle Assessment." *The International Journal of Life Cycle Assessment* 14(5): 392–400.

Kollmuss, A., H. Zink, and C. Polycarp. 2008. A Comparison of Carbon Offset Standards. WWF Germany.

Krokida, M., M. Taxiarchou, A. Politis, A. Peppas, A., and K. Kyriakopoulou. 2016. Life Cycle Assessment (LCA) on European Skimmed Milk Powder Processing Production Plant. *Scientific Bulletin. Series F. Biotechnologies* 20. https://doi.org/10.5281/zenodo.4319800.

McManus, M.C., and C.M. Taylor. 2015. The changing nature of life cycle assessment. *Biomass & Bioenergy* 82: 13–26. https://doi.org/10.1016/j.biombioe.2015.04.024

Nielsen, P.H., K.M. Oxenbøll, and H. Wenzel. 2007. "Cradle-to-Gate Environmental Assessment of Enzyme Products Produced Industrially in Denmark by Novozymes A/S." *The International Journal of Life Cycle Assessment* 12(6): 432.

Offset Your Emissions | The Gold Standard. n.d. Offset Your Emissions. Retrieved June 22, 2020, from https://www.goldstandard.org/take-action/offset-your-emissions.

Parker, L., and J. Blodgett. 2008. "'Carbon Leakage' and Trade: Issues and Approaches." Congressional Research Service.

Pearson, T.R.H., S. Brown, B. Sohngen, J. Henman, and S. Ohrel. 2014. "Transaction Costs for Carbon Sequestration Projects in the Tropical Forest Sector." *Mitigation and Adaptation Strategies for Global Change* 19(8): 1209–1222. https://doi.org/10.1007/s11027-013-9469-8.

Phan, T.-H.D., R. Brouwer, and M.D. Davidson. 2017. A Global Survey and Review of the Determinants of Transaction Costs of Forestry Carbon Projects. *Ecological Economics* 133: 1–10. https://doi.org/10.1016/j.ecolecon.2016.11.011.

Satterthwaite, D., G. McGranahan, and C. Tacoli. 2010. "Urbanization and Its Implications for Food and Farming." *Philosophical Transactions of the Royal Society B: Biological Sciences* 365.1554: 2809–2820.

Specht, L., and C. Lagally. 2017. Mapping Emerging Industries: Opportunities in Clean Meat. The Good Food Institute.

Smetana, S., et al. 2017. "Autotrophic and Heterotrophic Microalgae and Cyanobacteria Cultivation for Food and Feed: Life Cycle Assessment." *Bioresource Technology* 245: 162–170.

Steer, M. 2015. A Comparison of Land, Water and Energy Use Between Conventional and Yeast-Derived Dairy Products: An Initial Analysis. Report prepared for Perfect Day. University of the West of England, Bristol, UK.

System Models in ecoinvent 3. n.d. Retrieved May 31, 2020, from https://www.ecoinvent.org/database/system-models-in-ecoinvent-3/system-models-in-ecoinvent-3.html.

Tuomisto, H.L., and M.J. Teixeira de Mattos. 2011. "Environmental Impacts of Cultured Meat Production." *Environmental Science & Technology* 45(14): 6117–6123. https://doi.org/10.1021/es200130u.

U.S. Energy Information Administration. 2020. Nuclear Power Plants—Types of Reactors. https://www.eia.gov/energyexplained/nuclear/nuclear-power-plants-types-of-reactors.php.

U.S. Environmental Protection Agency. 2016. Understanding Global Warming Potentials [Overviews and Factsheets]. US EPA. Retrieved January 12, 2021 from https://www.epa.gov/ghgemissions/understanding-global-warming-potentials.

Waschulin, V., and L. Specht. 2018. Cellular Agriculture: An Extension of Common Production Methods for Food. The Good Food Institute. https://doi.org/10.1016/j.jclepro.2012.11.005.

Wilkes, A., S. Wassie, C. Odhong, S. Fraval, S., and S. van Dijk. 2020. Variation in the Carbon Footprint of Milk Production on Smallholder Dairy Farms in Central Kenya. *Journal of Cleaner Production* 121780.

Woldegebriel, D., H. Udo, T. Viets, E. van der Harst, E., and J. Potting, J. 2017. "Environmental Impact of Milk Production across an Intensification Gradient in Ethiopia." *Livestock Science* 206: 28–36.

## SUPPLEMENTS

### S1. The input amounts and GWP for products produced in a similar manner to cultured proteins

| Product | Primary Inputs | Amount per kg product | GWP per kg product | Source |
|---|---|---|---|---|
| Citric Acid | Energy | 21 kWh/kg product | 11.0 kg $CO_2$e/kg protein | Becker et al. 2019 |
| | Sugar | 1.07 kg/kg product | | |
| Cultured meat (19% protein) | Energy | 37–48 kWh/kg protein | 10–11.6 kg $CO_2$e/kg protein | Tuomisto 2011 |
| | Cyanobacteria | 3.78 kg/kg protein | | |
| Cultured meat (19% protein) | Energy | 55–88 KwH/kg protein | 12.1–23.15 kg $CO_2$e/kg protein | Tuomisto 2014 |
| | Cyanobacteria OR | 3.78 kg/kg protein | | |
| | Corn OR | 10 kg/kg protein | | |
| | Wheat | 10 kg/kg protein | | |
| Novozymes enzymes | Energy | NR | 1–10 kg $CO_2$e/kg enzyme | Nielsen et al. 2007 |
| | Starch | NR | | |
| | Sugar | NR | | |
| | Ammonia | NR | | |
| Novozymes calculations for fermentation-based protein production | Unknown | Unknown | 4.3 kg $CO_2$e/kg protein | Unpublished data |
| Pharmaceutical Enzymes | Energy | 36–58 kWh/kg enzyme | 16–25 kg $CO_2$e/kg enzyme | Kim et al. 2009 |
| | Soybean protein | NR | | |
| | Glycerol | NR | | |

| Product | Primary Inputs | Amount per kg product | GWP per kg product | Source |
|---|---|---|---|---|
| B-galactosidase* (lactase) | Ammonium Sulfate | 5.33 kg/kg enzyme | >5,000 kg $CO_2$e emitted/kg enzyme | Feijoo et al. 2017 |
| | Urea | 5.33 kg/kg enzyme | | |
| | Sucrose | 88.9 kg/kg enzyme | | |
| | Potassium phosphate | 10.6 kg/kg enzyme | | |
| | Water | >40,000 kg/kg enzyme | | |
| | Energy | >100 kwH/kg enzyme | | |

*This enzyme has a very energy- and water-intensive process, mostly stemming from steam production and purification/sterilization steps that are not represented in other LCAs listed here. At this time, we have no indication that cultured casein production would include these resource intensive steps, and therefore do not consider the water and energy inputs for this product as helpful comparisons.