Transforming Protein: Land-Use Implications of a Transition to Plant-Based Meat

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Master's Project Client: Client X

A project submitted in partial fulfillment of the requirements for the Degree of Master of Science in Environment and Sustainability

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April 2020

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Abstract

The burgeoning plant-based meat industry has demonstrated the potential for plant-based meat to provide a comparable consumer experience to animal meat with a significantly reduced environmental impact. This study explores the land-use implications of plant-based meat production under various adoption scenarios and ingredient mixtures.

A system-level model quantifies land that is both offset from beef and pork production and land that is potentially additive from ingredients grown in regions outside traditional animal agriculture supply chains. Coconut oil is explored as a potential high-risk ingredient due to it contributing additive land-use and being grown in sensitive biomes. GIS software was used to contextualize land-use requirements for the oil by comparing projections to existing suitable agricultural land in top producing countries and current production land area. Finally, a qualitative case study of potential risks and opportunities associated with relying on the oil was conducted to inform sourcing and ingredient panel strategies. There are several key takeaways from the analyses conducted:

1. Due to its much larger land-use footprint, plant-based displacement of beef products drive proportionally higher land-use benefits than that of pork.
2. Over 20 years, roughly 25% rate of animal-based meat displacement in the US will stabilize land-use associated with overall meat production in the country.
3. Under high market adoption, plant-based meat will require almost two million square hectares of land for coconut oil production in 20 years, or 55% of land currently used for coconut cultivation in the Philippines.

These findings signal that plant-based meat has significant land-use implications which can be realized under reasonably high adoption and over the long run. The industry would benefit from diversifying ingredients which represent additive land-use and potential supply chain risks. The research presented serves as a “living” model and foundation for future investigation into other ingredients used in plant-based meat products.

Introduction and Background

The global agricultural system is facing an immense, dual pronged challenge. With a rapidly increasing global population, the need to nourish society is set against the backdrop of the global climate crisis. The global food system is a major contributor to the climate crisis through various channels, including production and use of synthetic fertilizer, fuel consumption, livestock emissions, transport of products, and land clearing for increased production. At the same time, increasing demand for food will require greater land area to be cultivated absent dramatic improvements in yield or production technology (Alexandratos & Bruinsma, 2012; Searchinger et al., 2019; Tilman & Clark, 2014). Particularly harmful to the environment is the production of meat (Steinfeld et al., 2006).

The environmental impacts of animal agriculture, and in particular the beef industry, have been well documented (Rotz et al., 2019; Asem-Hiablie, 2018). Largely due to immense land and water requirements for production, as well as inefficient conversion feed inputs to consumable protein for humans, animal agriculture is a major contributor to the climate crisis we face as a global society (Steinfeld et al., 2006; Khan et al, 2019). Therefore, a clear need has emerged for consumption patterns to change as a piece of the solution to these tensions alongside improved yield and production technologies (Searchinger et al., 2019). Switching towards vegetarian alternatives is widely recognized as a means by which to achieve these goals (Dettling et al., 2016; Tilman & Clark, 2014). Increasingly, plant-based meat has emerged as a way of satisfying consumer demand for meat products, without the same devastating environmental impact (Heller et al.,2018; Khan et al, 2019).

The Rise of Plant-based Meat

Taste is a primary driver for meat consumption (Good Food Institute, 2019). Novel plant-based meat companies have been able to successfully mimic the taste and experience of meat through biomimicry in a way that previously wasn’t possible. Although plant-based meat alternatives have been on the market for many decades, the taste and texture of these products were not similar enough to real meat, limiting the plant-based market mainly to strict vegetarians. Moreover, improvements in taste and texture have been coupled with increased awareness of environmental impacts (Good Food Institute, 2019). This has propelled plant-based meat products into the mainstream and led to increasing demand for these products. It is important to note that while non-bio-mimicking, plant-forward products like tofu and jackfruit have also risen in popularity in recent years, for the purpose of this report, only bio-mimicking products will be considered.

The Need for a Systems-Level Analysis

An LCA conducted by Quantis demonstrates that on a unit comparison basis, plant-based meat requires 87% less water, and 96% less land to produce than animal meat, while generating 89% fewer greenhouse gasses (Khan et al, 2019). Similar results have been found industry wide (Heller et al., 2018). However, determining the land-use implications of a large-scale shift towards plant-based meat is not simply a question of proportionally scaling these results. A documented limitation of LCAs is that they often do not incorporate temporal effects (Stasinopoulos, 2011). As this system is highly dependent on adoption rates for a variety of plant-based products over time, it is important to consider temporal dynamics to get a comprehensive understanding of potential land-use impacts.

This study begins to address those questions by building on the aforementioned life cycle assessment with a systems level modeling approach. Therefore, this study took a systems-level approach using modeling software Stella and geo-spatial software GIS to explore systematic land-use impacts over a 20-year period. In addition, an in-depth qualitative study on coconut oil was conducted to contextualize these outputs as well as provide a structure for future analyses of current or potential plant-based ingredients.

Incorporation of Pork

The focus of this study is on the impacts of displacement of beef and pork consumption. In terms of land and water inputs, as well as emission productions, beef is one of the most detrimental products on the market. Pork is included largely because of the massive consumption level in markets such as China. While on a unit comparative basis, pork is less impactful than beef, the sheer volume of consumption, in large part driven by the Chinese population, displacing pork also has immense potential for reducing environmental impact of meat consumption. Therefore, plant-based protein manufacturers have developed plant-based pork alternatives, leading to its inclusion in this research study. In this report, pork and beef will be termed 'traditional' meat. The 'aggregate' meat market refers to the total demand for both traditional meat products and plant-based meat products.

Land Use in Agriculture

Land-use was chosen as the metric of study for this research for multiple reasons.
First, potential land constraints on food production as global population increase make reduction in land use intensity of food production critical. Second, the potential location-specific impacts associated with a transition to plant-based meat are largely unstudied. The carbon and climate related benefits of a plant-based diet are well documented, and the

benefits of carbon reduction are geographically dispersed. Land-use implications, including potential additional land-use change related to growing inputs to plant-based meat, poses environmental risks, as well as supply chain and reputational risks. Studying land requirements of projected future plant-based meat demand will enable companies to better source ingredients, thereby formulating products with the greatest environmental benefits.

In addition to addressing potential risks to plant-based meat companies, land-use is a potential proxy metric, able to provide broader insight into the aggregate environmental impact of a product. In a life cycle assessment focusing on the land-use implications of margarine, Canals et al. indicate that many impact categories follow a similar pattern to land occupation. While not a perfect proxy metric, land-use was determined to be valuable in identifying "hotspots" in the life cycle (2013). Similarly, land-use as a metric in this study will be used to identify hotspot ingredients, which may pose environmental, social, or business risks to the company.

Land use change, and land availability for food production has been widely studied. Much of the literature is focused on food security, quantifying potentially available agricultural land to meet growing global demand for food (Lambin, 2013; Mandryk et al., 2015). Additionally, these studies tend not to focus on the land use implications of specific food products or land availability in specific countries in a product supply chain. Furthermore, in quantifying land availability, they tend not to focus on limiting land use change for environmental purposes. Thus, in quantifying land for agriculture to inform future food security, they include all theoretically arable land, including virgin land that has conditions amenable to agricultural production. Rooted in the goal of limiting land use change, this research seeks to contextualize land use requirement projections using existing agricultural land.

Previous studies have explored the land use implications of plant-based meat alternatives at scale. In a narrow study of the impact of replacing a portion of Dutch meat consumption with plant-based alternatives, Temme et al. (2013) found that land use requirements are greatly reduced. However, the study focuses narrowly on reduction of meat consumption in women and predates the boom in plant-based meat alternatives intended to simulate animal meat. Gerbens-Leenes et al. (2002) developed a method for calculating land required to feed a population using demand in kilograms and land requirements per food in square meters per kilogram of food. The research contained in this report takes a similar approach to that of Gerbens-Leenes of applying land use requirements of individual ingredients and national level demand to determine land use for plant-based meats.

However, the Gerbens-Leenes study considers the whole household diet. Additionally, it does not model land use over time.

In general, research on the land use implications of plant-based meat have not considered the long-term land use implications of emerging meat alternatives, focusing instead on product level life cycle analyses comparing a particular meat alternative to traditional meat. Product level LCAs have been conducted for plant-based meat alternatives, such as one completed by Heller and Keoleian in 2018, demonstrating significant land use reduction compared to conventional meat. Similarly, in a product level LCA, Tuomisto et al. (2011) studied the land use implications of cultured meat, finding greatly reduced land use requirements compared to conventional meat. However, these are static product level LCAs and do not consider long term adoption scenarios in order to determine global land use implications. Furthermore, they tend to provide aggregate statistics for total land use, but do not disaggregate by ingredient or sourcing location of the ingredients. Thus, they say little about potential land use implications in specific locations. This study aims to build on product level LCAs of plant-based meats by incorporating dynamic variables over a 20-year time period and including location specific estimates at a regional scale of land use associated with ingredient inputs.

Project Assumptions

The research presented in this study is premised on the following underlying assumptions:

1. *Increased plant-based meat demand offsets demand for animal meat:* The model presented in this research assumes that increased market share of plant-based meat directly offsets market share for the equivalent animal-based meat product. For example, an increase of market share for plant-based ground beef directly offsets an equivalent amount of animal-based ground beef.
2. *The public's meat consumption habits will remain the same in the timeframe modeled:* The availability of plant-based meat will not increase a person's meat consumption. This assumption is an extension of the first assumption in that if an individual consumes ten pounds of beef in a year, the option to have a plant-based meat burger will not increase that figure, but rather a portion of that ten pounds will become plant-based.
3. *Our modeled is representative of plant-based meat:* In the systems modeling process, which involves a suite of ingredients and their corresponding land occupation figures, our fat, protein, and binder proportions are considered broadly representative of the plant-based meat industry as a whole.

Methodology and Results

This study took a three-stage approach to determine the potential land-use impacts of increased plant-based meat adoption. The first stage was to determine the total land required to meet the evolving aggregate meat market demand. The second stage was to analyze how those changes in land-use reconciled with the land under cultivation within the existing system serving the meat industry. The third stage of the study focused on the potential impacts of continued reliance on coconut oil as a key ingredient in a plant-based meat formulation. Special emphasis was placed on evaluating the business, land-use, and reputational risks of current sourcing from the Philippines. Mitigation strategies are also provided. The remaining sections outline the approach and results for each of the three stages.

Stage 1: Stella Systems Modelling

This study utilized visual programming software Stella (Systems Thinking for Education and Research) to model aggregate meat demand and land-use in the US and China. Stella has been used in previous studies to translate the implications of static product level life cycle assessments into a systems level assessment (Stasinopoulos et al., 2011). It offers three capabilities that were key to this project: 1) establishing non-linear relationships between variables; 2) modeling dynamic systems over time; and 3) visually representing the highly interconnected system. The Stella model was designed to answer the following overarching questions:

- How much of an impact do adoption rates have on total land-use?
- What is the minimum adoption rate required to stabilize and reduce total land-use?
- How much of an impact can ingredient mixture have on total land-use?
- Where is land-use change likely to occur and how much will be additive?
- How do these impacts differ between the US and China?

A detailed description of select model inputs can be found in Appendix A. The model projects land-use requirements for plant-based meat production over a 20-year timeframe under three adoption scenarios and various ingredient input combinations. It has four distinct modules:

1. *Demand*: The demand module models total aggregate demand for both animal and plant-based beef and pork. It then breaks down total demand into beef and pork, separating whole cuts and ground meat. To each subcategory of meat, a market

share adoption curve is applied to indicate what portion of demand is met by the plant-based meat equivalent. For all scenarios, aggregate meat market demand, representing the total demand for both animal and plant-based beef and pork products, starts at the same quantity demanded, and grows at the same overall rate. This in turn drives disaggregated animal-based and plant-based meat demand, according to the adoption rates for plant-based meat. The aggregate market growth rate and starting size remained constant across all scenario runs within each country.

In the US, the starting point for aggregate meat demand was approximately 24 billion kilograms, with an equal amount being attributed to pork and beef (Statista Beef, 2020; Statista Pork, 2020). The annual aggregate market growth rate was set at 2.5% by volume based on Grand View Research projections from now until 2025 (Grand View Research, 2019), after which the growth rate decreases linearly for the rest of the model simulation, reaching a 1.1% annual growth rate in the final year. This decrease in growth rate was used based on the lack of existing reliable growth projections beyond 2025, and the assumption that growth in demand for meat would not continue to outpace population growth indefinitely. The Chinese starting market size was approximately double that of the US, in line with numbers reported by Statista (2017). The same initial annual growth rate was used for China, however, the rate remained at 2.5% for the rest of the model simulation under the assumption that per capita meat demand in China will continue to rise with increasing wealth.

Aggregate meat demand was then disaggregated into whole and ground beef and pork. To determine the quantity of plant-based meat demanded, market share adoption curves were applied to the disaggregated meat categories. These curves represented the proportion of demand for each meat category met by plant-based meat. Each cut and type of animal-based meat and the corresponding plant-based alternative was assigned an individual adoption variable in the model. This is because plant-based ground pork, whole cut pork and whole-cut beef have not yet been released in the market. Plant-based ground beef is already available to consumers, while the others are not. In each scenario, the same adoption curve was applied to all four versions of plant-based meat (whole and ground beef and pork) with a time delay for each unavailable type of plant-based meat.

Appendix A.i includes screenshots of the market share adoption curves applied. The three adoption scenarios tested in this study were:

a. Market Adoption - based on market projections for plant-based meat sales by volume (Arizton, 2019). The report projects roughly 33% year over year increase in volume of plant-based meat sold in the US through 2025. Limited information was available regarding longer term projections for the plant-based meat industry. Thus, for the purpose of this study, the 33% percent growth rate was carried forward for the duration of the 20-year model projections until reaching 100% market share.

b. High Adoption - The High Adoption scenario was designed to represent a rapid technology adoption curve often observed with the introduction of transformative technologies. This scenario reaches that benchmark rapidly within 10 years

c. Low Adoption - The Low Adoption scenario was based on plant-based milk market share of roughly 15% (Good Food Institute, 2019), a target which was assumed to be reasonable for plant-based meat alternatives to reach. Under the Low Adoption scenario, plant-based meat plateaus at the level.

2. *Animal agriculture land-use:* Land-use required to produce a kilogram of beef and pork was disaggregated into grazing areas and feed production land based on life cycle assessments of the two animal products. Approximately 86% of land used to produce beef is grazing land, with the remaining 14% being used to grow feed (Khan et al, 2019).

   One of the main reasons why pork is so much less land intensive than beef is because hogs do not require grazing land. For pork, land used to grow feed makes up approximately 95% of total land use, while only 5% of the land is used to physically keep the animals (Flachowsky, Meyer & Südekum, 2017). These land-use intensities were then applied to quantity demanded of each type and cut of meat. Ground products were assumed to make up 42% of aggregate meat demanded, with the remaining 58% pertaining to whole cuts (Davis & Lin, 2005).

3. *Ingredient mix:* The ingredient panel module represents the type and amount of ingredients used in plant-based meat products, which in turn impact the amount and geography of land-use. Plant-based meat was disaggregated into five constituent components based current plant-based meat formulas and projected formula requirements for whole cuts, including: coconut-like oil, sunflower-like oil,

protein, mycoprotein, and flavoring. The ingredient mix for pork and beef differ slightly, with pork containing less flavoring. Whole cuts were modeled such that mycoprotein comprises a significant portion of the protein content. This study did not consider water content or non-significant flavoring ingredients.

To determine the effect that different ingredient mixtures can have on land-use, a variety of alternative ingredients were included in the model. Alternatives were offered for four of the main ingredients currently used: coconut oil, sunflower oil, soy protein and potato protein. Potential ingredient combinations were designed to maximize or minimize total and additive land-use to enable a full assessment of the impact that ingredient mixture can have. It is important to note that some of these combinations may not be realistic. The main purpose of this exercise was to demonstrate the possible effect that a different ingredient mixture could have and not to explore probable ingredient mixtures and their impacts. Table 1 contains the combinations of ingredients tested. Percentage breakdowns by mass are based on approximation of current formula. The remaining mass is assumed to be water and non-material flavoring agents.

Table 1. Ingredient combinations

	Coconut-like Oil ([redacted]%)	**Sunflower-like Oil ([redacted]%)**	**Protein & Binding Agent ([redacted]%)**
Base Case	Coconut	Sunflower	[redacted]% Soy, [redacted]% Potato
Minimize total land-use	Coconut	Canola	Soy
Minimize additive land-use	Soy	Cotton	Soy
Maximize total land-use	Corn	Cotton	Potato
Maximize additive land-use	Palm	Deccan Hemp	Potato

4. *Land-use by region:* This portion used the quantity of plant-based meat demanded, the amount of each type of ingredient needed per kilogram of product, and the top regions where each ingredient is produced to determine the projected land-use in each region for plant-based meat. These regional projections are then aggregated into either offset or additive land-use. Offset land-use includes two categories of crops: 1) those that are included in the plant-based meat mixture and also used for animal feed; and 2) those that are included in the plant-based meat mixture and are grown in countries where animal feed production or large scale beef and pork agriculture occurs.

Potential additive land-use includes land required to produce ingredients not included in the existing animal agriculture supply chain and that are sourced from regions not prominent in cattle and pork production. Coconut oil, which is largely sourced from Southeast Asia, is a prominent example of an ingredient with potential additive land-use implications. Details regarding land-use inputs for each ingredient and top production regions for each crop can be found in Appendix A.ii.

Results of the Stella Model

The model results consist of four key findings: 1) systematic land-use benefits from plant-based meat will only be realized if significant adoption takes place and will only be experienced in the long-term; 2) while ingredient mixture has a minimal impact on total land-use patterns, it does wholly determine whether land-use is off-set or additive; 3) due to comparatively higher demand for pork in China than in the US, the potential land use benefits of plant-based meat adoption are proportionally less, however, they are greater in absolute terms due to China's larger population; 4) the minimum adoption of plant-based meat needed to stabilize land-use in the time-period is roughly 25% for the US market.

The table below demonstrates the vastly different land-use impacts of the three adoption scenarios applied. It can be seen that the land-use benefits of plant-based meat adoption become meaningful midway through the time period analyzed. For the purposes of this study, land-use savings refers to any land that would have been used to meet beef and pork demand for the US market had plant-based adoption not taken place.

Table 2: land use savings from plant-based meat adoption

Adoption scenario	Land-use savings in 5-years	Land-use savings in 10-years	Land-use savings in 15-years	Land-use savings in 20-years
Market Adoption	1%	5%	19%	55%
Low Adoption	2%	6%	11%	13%
High Adoption	14%	53%	83%	90%

Secondly, there is a tension between minimizing total land-use for plant-based meat products and minimizing additive land used, which is represented in the table below. The study assumes that minimizing additive land is desirable because doing so could mitigate biodiversity loss and other social issues. For the purposes of this study, additive land refers to all land that is not currently part of the US meat value chain. The model indicates that it is not possible to both minimize total and additive land use, based on the ingredient panel considered. This presents a trade-off to consider. The ingredient mixture designed to minimize the amount of additive land-use lead to 240% more total land-use than a mixture designed to minimize total land-use. Conversely, the ingredient mixture designed to minimize total land-use led to 529% more additive land-use than the minimizing additive land-use mixture. Specific ingredient lists are detailed in Table 1.

Table 3: land use associated with ingredient combinations

Ingredient Mixture	**Additive (M Ha^2)**	**Total land-use (M Ha^2)**
Minimize total land-use	3.27	8.77
Minimize additive land-use	0.52	19.12

While the average American consumes an approximately equal amount of pork and beef in terms of weight, the average person in China eats roughly 3.5 times as much pork as beef. As pork is far less land-use intensive than beef, the land-use benefits of a switch from animal-based pork to plant-based pork will be less. Assuming the same Market Adoption scenario of plant-based meat in both markets, total land-use savings from shifting Chinese demand will be approximately 50% compared to 55% in the US. It is important to note that because China consumes approximately double the amount of pork and beef in terms of weight as the US does, land-use savings from increased adoption of plant-based meat adoption in China would lead to higher absolute land-use savings than in the US. This translates to 98 million hectares being saved from Chinese adoption and 62 million hectares being saved from US adoption. Given the size of both countries' meat markets, the US savings are proportionally greater.

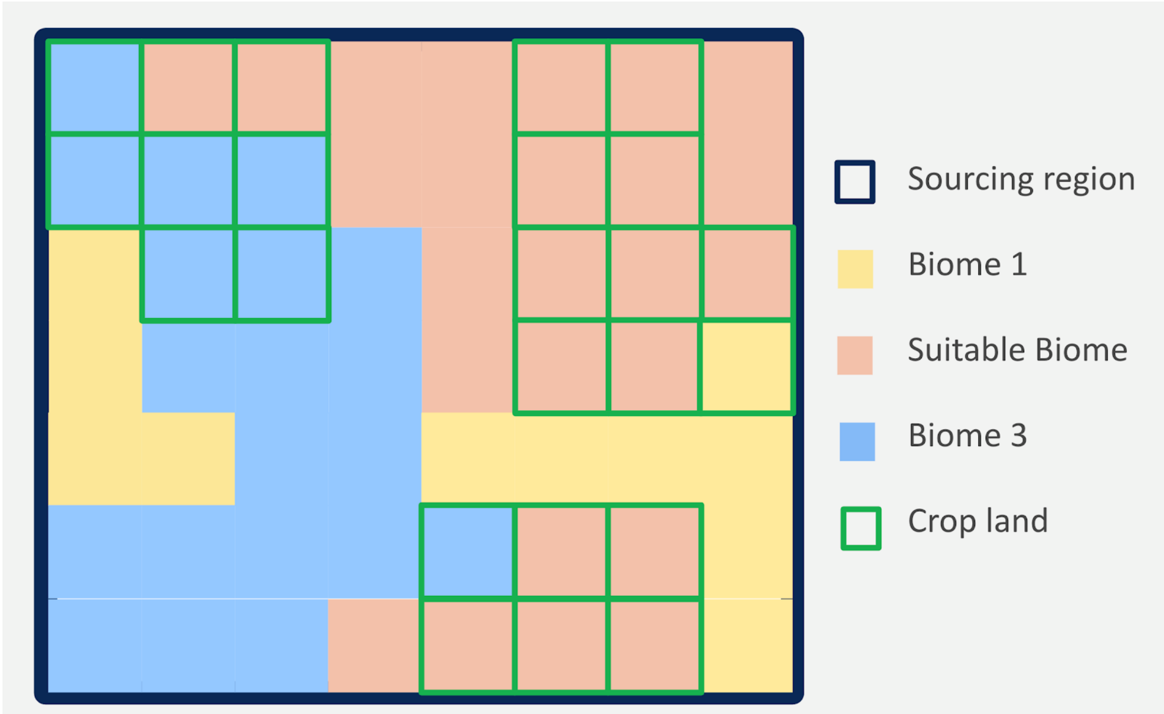
Finally, to stabilize total land-use over the time period, a minimum adoption of approximately 25% in the US would be needed. While total land-use reduction would be the ultimate goal, for the purpose of this study it is assumed that aggregate meat land-use stabilization would be the first step in achieving systematic land-use benefits. For the Chinese market, this minimum adoption is closer to 30%.

Stage 2: GIS Analysis

In order to contextualize the Stella model output for land area required to produce plant-based meat, analysis of suitable land for crop production was conducted using ArcGIS software. For this study, GIS analysis was conducted only in relation to the cultivation of coconut based on its potential for additional land-use change and impacts on sensitive biomes. Additionally, the GIS analysis was focused on quantifying agricultural land that is already under cultivation and did not quantify all land that could theoretically be converted to agriculture. This study analyzed the land of the top two coconut-producing countries, the Philippines and Indonesia, in addition to India and Brazil. The latter were included based on high potential production capacity.

The analysis consisted of layering raster data for current agricultural land with biome raster data within a specific country. Current global agricultural land area extent was obtained from Global Food Security-Support Analysis Data produced by NASA and the United States Geological Survey. Biome data was used to delineate areas theoretically suitable for production of coconut and was obtained from The Nature Conservancy. Based on the location of coconut production in the Philippines and Indonesia, it was determined that moist tropical broadleaf forest biomes were most suitable for coconut production. Utilizing these datasets, and the zonal statistics capabilities in the ArcGIS suite, maximum theoretical land available for coconut production without conversion of virgin land was obtained. Appendix B details the process used to quantify theoretical suitable agricultural land available for coconut production in these countries and images of input layers. Figure 1 contains a conceptual model of the GIS process utilized.

Figure 1. Conceptual model of GIS analysis



Intent of the GIS analysis is to quantify existing agricultural land in a suitable biome for a specific crop within a sourcing region. In this model, these areas are represented by the orange cells outlined in green.

Results of the GIS Analysis

Table 4 contains high level results of the GIS analysis, indicating consequential findings related to reliance on the Philippines for coconut oil. Notably, under the High Adoption scenario in the long run, plant-based meat will require 55% of current land devoted to coconut production in the Philippines (FAO STAT, 2018). That amount of land represents 26% of all agricultural land in the appropriate biome for coconut cultivation in the Philippines. These findings signal that the industry must diversify its supply chain or oil inputs. While the other three countries analyzed have significantly more land available for potential production, existing production and export capacities remain far lower.

Table 4: Land use requirements for coconut as a percentage of exist coconut production and available agricultural land – 20 year high adoption scenario

Country	**Philippines**	**Indonesia**	**India**	**Brazil**
FAO coconut production 2018 (Ha^2)	3,628,134	3,247,986	2,098,946	198,715
Ag land in suitable biome (Ha^2)	7,544,700	35,049,900	60,130,300	68,143,100
Plant-based meat's toll on existing production in 20-yr high adoption	55%	61%	94%	997%
Plant-based meat's toll on available coconut land under 20-yr high-adoption	26%	6%	3%	3%

Stage 3: Coconut Case Study

Economic considerations

Economic factors are important to consider when looking at coconut production in both the Philippines and Indonesia because they provide a basis for understanding incentives for farmers to produce the crop. Commodity pricing for coconut products has widely varied for the past 20 years, with large peaks and valleys making profitability volatile for producers (*Index Mundi – Coconut oil, n.d.*). Appendix C.i shows how the historical pricing for coconut has changed over the past 20 years, with inconsistent price gains. When comparing coconut oil pricing to a crop like palm oil, there is a similar amount of variability in pricing with peaks and valleys. However, palm oil, as seen in Appendix C.ii, has made modest gains, and may be a more attractive crop economically to producers.

In addition to the challenges unpredictable commodity pricing may give producers, the economics for individual smallholder farmers are often unfavorable when farming coconut. Individual farmer income varies depending on how the coconuts are sold (i.e. sold as copra or whole nuts) and how far the farmer must travel to gain access to the market (Pabuayon, I. M., Medina, S. M., Medina, C. M., Manohar, E. C., & Villegas, J. I. P.,2008). Farmers have limited participation in the coconut value chain compared to processors and traders, giving them much lower market power (Pabuayon, I. M., Cabahug, R. D., Castillo, S. V. A., & Mendoza, M. D., 2009). Although there are instances in which the farmer's value share of a product's profit may be relatively high, this doesn't necessarily translate to high farm income. Most farmers have small farm sizes, low productivity and therefore limited surplus (Pabuayon, I., et al, 2009). Of the 12 million hectares of planted coconut crops, 96% of farmers tend to farm less than 4 hectares (Abdulsamad, 2016). The low productivity and low pricing leads coconut to produce less oil and income compared to oil palm (Adkins, S. W., Foale, M., & Samosir, Y. M. S.,2006). A study commissioned by the International Coconut Forum found "Coconut produces 0.53 t/ha of oil (averaged over the total area of palms in Indonesia), valued at US$423/ha, while oil palm produces 3.17 t/ha, valued at US$1,729/ha" (Adkins, S., et al, 2006). Finding more equity in the coconut supply chain for small-holder farmers, in addition to adopting value-added activities and practices is needed in order to make coconut production a more attractive pursuit.

Social Factors

Smallholder farmers play a crucial role in current coconut production, with a large number of farmers cultivating a small area of land. Structurally, this shows that smallholder farmers make up a large quantity of stakeholders upon whom the industry is dependent. This also illustrates the expansiveness of the work that must be done to ensure that scaled efforts to change or grow the industry do not negatively impact these farmers. Similarly, a large scale of intervention is needed to drive positive impacts on yield and subsequently on the income of smallholder farmers to grow the industry.

These farmers face a number of challenges that hold back their ability to gain financially. As farmers of other crops have benefitted from investment in yield, coconut farmers have supported an industry that has not seen an increase in production since the 1970s as demand trailed off given coconut oil's direct competition with crops like palm oil (Abdulsamad, 2016). This lack of investment and infrastructure has negatively impacted the ability of coconut farmers to access higher-yield varietals. In the Caribbean, a region where multiple countries must collaborate to drive such investment and shared knowledge, there are unique challenges such as the need to collectively fund research and find legal pathways to share coconut embryos between countries in reaction to agricultural safety regulations (Abdulsamad, 2016). This type of challenge may not exist for countries with either high enough current production or high enough potential production given our GIS analysis of viable productive land for coconut farming.

It is important to consider the position smallholder farmers have in the overall value chain. Appendix D contains a figure from the examination of the coconut value chain for the small Caribbean economies by Abdulsamad (2016). This figure shows the steps involved in the manufacturing of coconut oil from the inputs of finance, land, water, agrochemicals, seedlings, and R&D. From those initial inputs, mature coconuts are produced, which are then sent to primary processing, advanced processing, and manufacturing before reaching the end market through inclusion in branded products created by lead firms. Naturally, at each step along this path, value is claimed by the firms providing a service. Given the relatively large quantity of smallholder farmers relative to processors and manufacturers, it is evident that smallholder farmers' relative market power is more diffuse, thus they are unable to effectively bargain for a higher percentage of the value provided to consumers by the lead firms' branded products.

Looking at the beginning of the value chain, there are also clear challenges for smallholder farmers related to inputs they may be unable to provide themselves as production expands: seedlings, R&D, and agrochemicals. While limited examples of expansion exist for coconut oil production, we found a comparable example of palm oil industry growth in Palawan, an island in the Philippines. This project started with the first seedlings planted in 2007 and harvesting commenced in 2011 (Larsen et al., 2014).

This project resulted from growing private sector interest and was "part of the national government's objective to reduce palm oil imports, seize production shares in the international market and, in general, modernize the agricultural sector" (Larsen et al., 2014). The provincial government promoted the plan based on an assumption of "abundant idle lands" and the opportunity to improve rural livelihoods (Larsen 2014). The "vast majority" of farmers taking part in this project were agrarian reform beneficiaries, individual farmers who were granted land titles by the "Department of Agrarian Reform (called Certificates of Land Ownership Award – CLOA)" (Larsen et al., 2014).

The project was driven by contractual arrangements between farmers and a private company named AGPI (Agumil Philippines, Inc.) and these arrangements were viewed positively by the government as AGPI was viewed as filling a gap in credit and market access that limited the ability of farmers to capitalize on the land they were awarded (Larsen et al., 2014). The farmer cooperatives provided land and labor, AGPI provided seedlings and technical knowledge; however, these agreements placed the financial and managerial risks with cooperatives and gave control over land-use decisions to AGPI (Larsen 2014). The key social grievances related to these contracts were: contractual deception, deepened poverty, and indigenous peoples' land dispossession (Larsen et al., 2014). The amount of decision-making power given to AGPI related to the use of the land, and AGPI's key role in setting budgets and loan amounts made farmers vulnerable as this land is their key asset and an inability to pay AGPI on time for its services resulted in a compounding interest rate; further, allegations of verbal agreements not reflected in formal documentation were noted and "ignored" (Larsen 2014). In the process of expanding this project, AGPI entered into contracts with farmers who did not have formal land titles and land acquisition took place without consultation with groups who had legitimate land claims (Larsen 2014). These combined led to the primary negative outcomes listed above.

Political Dynamics

To examine the potential impact of political factors, this past example of land-use expansion and government intervention, as well as more current efforts are reflective of how governments may approach an expansion of coconut oil cultivation. The prior example in Palawan provides some guidance. The government's goal to expand palm oil production led to private business interest in executing on this goal. In the process, it can be argued that smallholder farmer needs were held secondary to the larger businesses taking part in these projects. The oversight that would have reigned in some of the harmful outcomes appear not to have taken place. Larsen and team noted that cooperatives "made repeated, unsuccessful attempts to submit Board resolutions to AGPI" and indigenous communities "filed complaints with sworn affidavits to the provincial government" related to palm oil land cultivation on their land; however, "for the most part, government offices have not intervened" (Larsen 2014). This has led to nongovernmental actions and greater coalition building by smallholder farmers, indigenous people, and civil society which is now advocating for a moratorium on further palm oil expansion (Larsen 2014).

This example helps to reveal the potential way in which political factors will play a role in the expansion of coconut oil and reveals the need for plant-based meat brands to leverage their influence to drive outcomes that sustain smallholder farmer incomes both from an equity perspective and from the perspective of the essential nature of this partnership to assure continued expansion of the coconut oil industry over the long run.

Today, Agriculture Secretary of the Philippines William D. Dar is pursuing three measures to develop the coconut oil industry. First, National Product Standards have been developed for food and non-food products related to coconut production to ensure high quality standards (DA Communications Group, 2020). Second, the percentage of coco methyl ester blend in biodiesel has been increased to address falling prices of copra (DA Communications Group, 2020). Third, a general call for modernization and industrialization of the local coconut industry in accordance with "the 'new thinking in agriculture principle' of the Department of Agriculture'' (DA Communications Group, 2020). Further actions for immediate execution consisted of expanding coconut production and replacing senile coconut trees with high-yielding varieties, enhancing of farmers' access to planting materials and leveraging the formation of cooperative businesses to increase the number of coconut processing plants (DA Communications Group, 2020). Through this plan announced in February 2020, it is evident that countries are working now to expand their coconut production, indicating a nearing crucial period for the plant-based meat industry, and other key current and future coconut oil stakeholders, to influence the expansion of coconut oil production to enable sustainable outcomes for the long term.

Environmental Impact

Compared to other oils produced in tropical regions, coconut appears to have a relatively low environmental impact due to low investment in commercializing the crop. Coconut's environmental impact is largely viewed through a soil erosion lens and its potential to disrupt fragile surrounding ecosystems (Pabuayon, et al., 2008). Important mitigation efforts include using cover crops or intercropping techniques to prevent environmental damage (Pabuayon, et al., 2008). In the Philippines, a source of environmental concern also comes from a scarcity of wood. When coconut farmers' incomes are low enough, they will often cut coconut trees for commercial sale of lumber (Pabuayon, et al., 2008). About 30% of coconut lands in the Philippines are in mountainous areas, so when trees are cut for lumber it could lead to a deterioration of the industry along with contribution to soil erosion (Pabuayon, et al., 2008).

When managed responsibly, however, coconut often has a low environmental impact on the ecosystem around it, especially relative to other crops. Coconut trees are permanent crops, not requiring replanting each year, contributing to soil health and stability. Current harvesting methods are low-impact, which primarily rely on smallholder farmers and laborers knocking the coconut from the tree to the ground. With additional investment into this industry through new varietals, fertilizers, and harvesting techniques, the environmental impact will need to be reassessed.

Recommendations

Based upon the results from the Stella model and the GIS data, and in conjunction with the risk factors outlined, there are three recommendations the plant-based meat industry should examine when looking at the future of coconut within its supply chain.

Recommendation 1: Partnerships

The first recommendation is to look into partnerships, in the form of corporate partnerships, nonprofit organizational partnerships or a combination of both. When looking at how brands may leverage a corporate partnership there are several advantages to working with a large corporation. Corporations bring transparency to the supply chain, increase investment where it may be lacking and potentially develop programs that work with farmers.

A current example of a large corporation that is working on the coconut supply chain is Cargill's partnership with both P&G and BASF on their initiative to drive sustainable certified coconut oil in the Philippines and Indonesia. Through this partnership, Cargill is addressing the main farmer challenges that stand between improving their livelihoods. These challenges include: lack of economies of scale, lack of financing or resources, and a rigid supply chain that lacks transparency. Although a large corporate partnership can provide many advantages such as institutionalized knowledge and the ability to make rapid change, due to the relative size of plant-based meat manufacturers and sourcing needs, it would likely be difficult to gain influence or partnership status.

Plant-based meat brands also serve to benefit from developing partnerships with nonprofit organizations supporting the development of smallholder coconut farmers and their communities. An example of this approach is Vita Coco's partnership with HOPE as part of the Vita Coco Project. The project's mission is to raise one million people in coconut farming out of poverty by giving a portion of profits back to coconut farming communities, helping farmers increase annual yields and improving community well-being ("Vita Coco Project", 2020). HOPE helps farmers sustainably increase yields by providing seedlings, and training farmers on intercropping and fertilizer use ("Friends of Hope," 2020). HOPE also impacts the community around coconut farmers through a focus on education by building classrooms, and providing scholarships and microloans ("Friends of Hope," 2020). This type of partnership helps brands connect directly and transparently with the smallholder farming community by leveraging existing farmer trust in a nonprofit partner. Potential drawbacks in pursuing these partnerships center around coordination costs to 1) ensure the nonprofit's activities reflect a given brand, their mission, and their business goals appropriately; and 2) expand the number or scope of nonprofit partners in tandem with any expansion of sourcing to new geographic areas.

Certification partners are another recommended partnership to build consumer trust in the equity and transparency in the plant-based meat value chain. Lack of transparency into farmer equity can be addressed through certifications such as Fair Trade Certification and Fair for Life certification which have been pursued by brands like Nutiva coconut oil (Fair Trade), Harmless Harvest (Fair for Life), and Zico (launched Fair Trade line) (Zico Beverages LLC, 2015; Nutiva, 2018; Siegner, 2020). While adding certification labels can help build trust with some consumers, the adequacy of a single label will likely be brought into question by some of the more educated consumers, necessitating a broader communication approach.

Recommendation 2: Geographic Diversification

There may be taste and textural elements that make replacing coconut oil difficult without compromising product quality. In this case, diversifying regional sourcing of coconut oil is a key risk mitigation strategy. Doing so will help eliminate concerns over land constraints in the Philippines and neighboring Indonesia while not relying on technological innovation to increase yield in those countries. While adding Indonesia as a secondary country may help in the short-term, many of the same risks that exist in the Philippines are shared by Indonesia. Most notably, as it relates to land-use, both countries have limited capacity to increase coconut oil production without clearing forests or mangrove areas for additional farmland.

Therefore, it may be advisable for plant-based meat manufacturers to look elsewhere to diversify their supply chains. Larger countries such as India and Brazil have begun to increase their production of coconut oil, however, it is unclear whether those countries will continue to scale to a level needed by the plant-based meat industry. Alternatively, brands can look to smaller regions where they may have outsized influence and bargaining power, in addition to being able to lead sustainability initiatives in those areas as it builds out the supply chain.

One such region examined during this study was the Caribbean. Countries in the Caribbean represent a consortium of farmers, processors, and exporters that are in significantly closer proximity to the key US ports than are the Philippines and Indonesia. As some countries, such as Guyana, look to wean themselves off a reliance on sugar exports, they have dramatically increased coconut production and may look to play in global markets. As the region's production increases and its supply chain develops, it may be able to service plant-based meat's needs for the next five to ten years. (Abdulsamad, 2016) Given the relative immaturity of the supply chain, a plant-based meat manufacturer could play a large role in helping shape it in a way that is beneficial to the company and maintains smallholder farmer equity as a priority.

Recommendation 3: Ingredient Diversification

Based on the projected amount of coconut oil that would be required to meet market demand, the industry would be heavily indexing in one ingredient that is produced in an additive land region. Looking to other oils that could potentially be used in tandem, or substituted for coconut oil, will minimize supply chain risks.

Investigating the use of other oils would help alleviate the demand for coconut production that is sourced from the Philippines and Indonesia, both of which will have constraints on land available for coconut production. Given the historical lack of investment in coconut yield improvements, investing in secondary ingredients could turn out to be a more capital efficient strategy. Additionally, an alternative oil may also have lower land-use.

Risks to this strategy largely come from product integrity. Changing the oil that is used in plant-based meat products to something other than coconut may have taste and texture implications. Although investigating alternative oils may yield small sustainability gains from a land-use perspective, moving land-use change from one ingredient to many may make sustainability actions more challenging from a resource and partnership perspective.

Limitations of the Research

Modelling Analysis

The Stella model constructed for this research produces robust projections of land use necessary to meet plant-based meat demand, drawing on extensive research on crop yields and sourcing regions, as well as, projected demand for meat. However, the modelling process required distillation of a highly complex food system in order to produce these results. As a result, the model faces certain limitations that should be explored in further research.

First, the model does not consider pricing dynamics of animal meat or plant-based meat inputs over the course of the 20-year modelling period. Changing prices is likely to impact both the quantity of types of meat demanded, as well as potential ingredient mixtures to produce plant-based meat. Absent pricing dynamics of crop inputs, each combination of ingredients is equally likely from a cost perspective, and the mixture can therefore be determined solely based on desired flavor, texture, or environmental properties. Furthermore, pricing dynamics are also likely to impact the sourcing regions included in the study. Specifically, the value of a crop in comparison to alternative crops is likely to determine whether or not farmers grow the ingredient, thereby either displacing crops on existing agricultural land, or contributing to additional land use change to meet demand, thereby impacting whether or not land use is additive or offset in nature. Incorporating feedback loops of increased demand and increased prices for inputs will simultaneously increase the complexity and robustness of the model.

Second, the model does not include dynamic variables to reflect improved yield. Instead, yields are static over the course of the modelling period. This decision was rooted in a few assumptions and constraints. First, for many crop inputs, particularly those grown in western countries, it was assumed that industrial agriculture has achieved high yields, and that improvements are likely to be marginal in nature. Second, limited work has been conducted on improving yields of certain crops such as coconut, thereby limiting information available to project improvements. These two factors led to the use of static yields and land use intensities. Incorporating yield improvements into the model using proxy crops where necessary or projections rooted in literature would be one means by which to improve land use projections.

Third, some ingredient combinations modelled may not be feasible in reality. All plant inputs modeled can be used to produce the fat, protein, or binder component they correspond to in the model. However, with target flavor and texture experiences, as well as prices and environmental impact, certain ingredients may not be realistic to use. An ingredient may prove to be cost prohibitive or result in a poor eating experience. Modelling probable ingredient combinations could improve the robustness of ingredient combination conclusions.

With regard to GIS modelling, other crops and commodity pricing are not incorporated into the quantification of available land. The analysis is intended to quantify existing agricultural land theoretically suitable for coconut production. However, absent pricing information between crops, the GIS analysis does not indicate whether or not crops will be displaced within existing land, or whether further land clearing will occur as a result of increased coconut demand.

Coconut oil risks

Our research on risks related to land use expansion to meet growing coconut oil demand also faced limitations. First, due to the value of intellectual property, the research team had limited access to detailed information about the current day plant-based meat supply chain operations or plans for use of future ingredients. We also faced challenges related to coconut oil-specific research availability. Given its relatively small size compared to other oil markets such as palm, there have been limited studies conducted on coconut oil supply chains and their environmental impacts. The research team used some studies of palm oil as proxies for coconut oil given the similarity in product and cultivation regions.

Implications and Next Steps

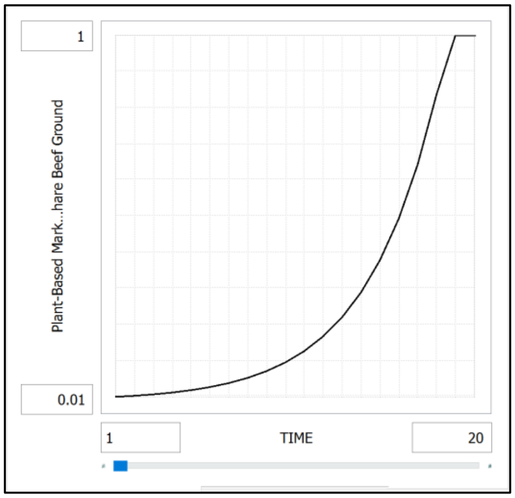
Decisions by plant-based meat manufacturers have significant consequences on global agricultural land-use. The research and analysis conducted over the duration of this project indicate that there are three key factors that will ultimately drive results: 1) the rate at which consumers adopt plant-based meat; 2) focusing on beef displacement over other meats; and 3) being mindful of areas in which sourcing efforts might be increasing land-use versus offsetting it. By optimizing these factors, the research conducted signals that by achieving roughly 25% market share of meat demand in the US, the plant-based meat industry can effectively stabilize or begin to reduce agricultural land-use that goes toward US meat production, including land both for grazing and feed.

It is recommended that plant-based meat manufacturers rely on the research presented, the Stella model provided, and the three-step approach outlined to build upon the analysis and initial findings. While we have used coconut oil in Southeast Asia as one example to examine, companies would benefit from extending the research presented to their existing set of ingredients and their most likely substitutes. By making informed adjustments to the Stella model inputs, leveraging GIS data, and weaving in internal sourcing expertise and supplemental research, plant-based meat manufacturers can reveal key insights. They can uncover which combinations of ingredients and sourcing environments may produce optimal outcomes for their business, for land-use, and for the suppliers upon which they rely. Doing so will help inform their strategy as they examine near-and-long-term growth plans and continue displacing animal agriculture and maximizing its environmental impact.

Appendices

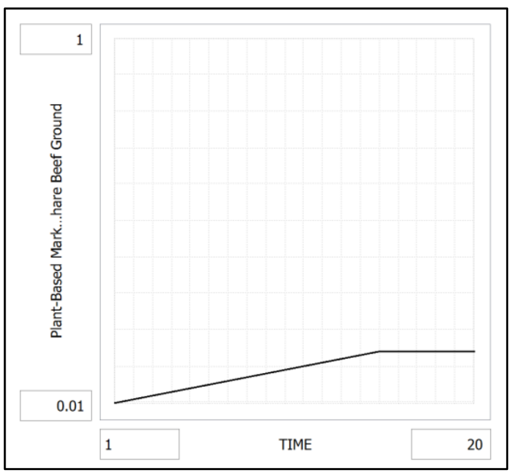
Appendix A: Stella Modelling

Appendix A.i: Plant Based Meat Adoption Scenarios



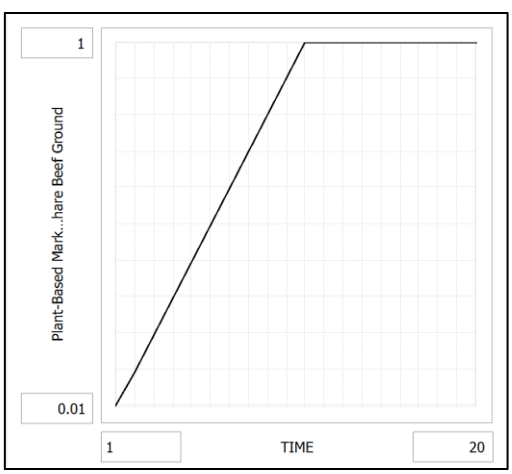
Market Adoption

The Market Adoption curve was based on market projections for plant-based meat sales by volume from Arizton. The report projects roughly 33% year over year increase in volume of plant-based meat sold in the US through 2025 (Arizton, 2019). Limited information was available regarding longer term projections for the plant-based meat industry. Thus, for the purpose of this study, the 33% percent growth rate was carried forward for the duration of the 20-year model projections until reaching 100% market share.



Low Adoption

The Low Adoption scenario was based on plant based milk market share of roughly 15% (Good Food Institute, 2019), a target which was assumed to be reasonable for plant based meat alternatives to reach. Under the Low Adoption scenario, plant based meat plateaus at the level.



High Adoption

The High Adoption scenario was designed to represent a rapid technology adoption curve often observed with the introduction of transformative technologies. This scenario reaches that benchmark rapidly within 10 years.

Appendix A.ii: Ingredient Inputs

Alternative ingredients were offered for four of the main ingredients currently used in plant-based meat formulations. We assumed proportions for all alternatives would be the same as the corresponding ingredient in the current formulas. These amounts differed slightly depending on the type and cut of meat. The full list of ingredients considered can be found below. For each ingredient, the top four producing countries of the ingredient were listed. However, for some cases majority or all production took place in fewer than four countries. In other cases, relatively small amounts of an ingredient were sourced from a very wide range of countries. In cases like this, regions, rather than countries, were used. For ingredients which can also feed-crops, no sourcing region was listed because this was counted towards off-set land-use.

To determine yield, the percentage of the crop made up by the desired component (protein or oil) was later applied to the yield of the crop as a whole in cases where the yield for the oil or protein alone could not be found.

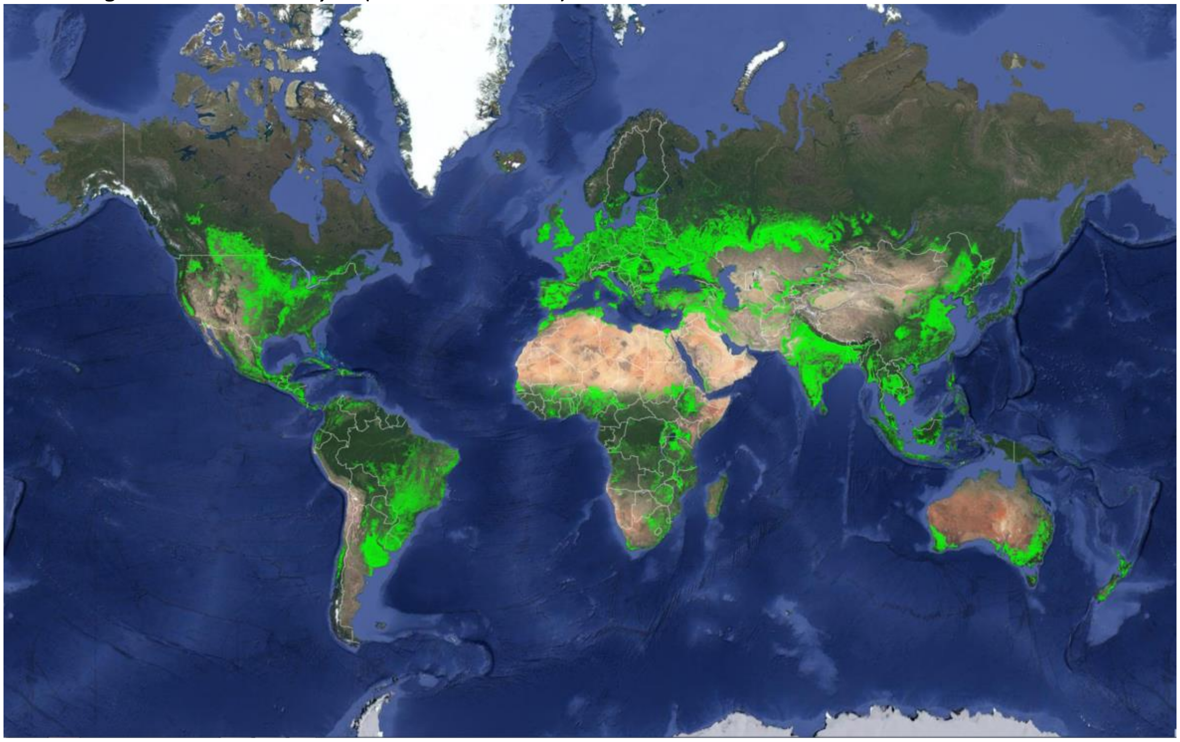
Ingredient	Substitute for	Purpose	Yield (m2/kg) *numbers are derived from the sources provided based on mass allocation for the component of the crop desired	Top producing country
Coconut Oil	-	Fat	4.425 (Hossain and Davies 2009)	Philippines, Indonesia, India, Brazil (FAO Stat, 2018)
Palm Oil	Coconut Oil	Fat	52.910 (Hossain and Davies 2009)	Indonesia, Malaysia (FAO Stat, 2018)
Jojoba Oil	Coconut Oil	Fat	6.545 (Hossain and Davies)	North America (FAO Stat, 2018)
Corn Oil	Coconut Oil	Fat	68.966 (Hossain and Davies)	-
Soybean Oil	Coconut Oil	Fat	26.667 (Hossain and Davies)	-
Sunflower Oil	-	Fat	12.5 (Hossain and Davies)	Russia , Europe, Argentina (FAO Investment Center Division, 2010)
Cotton Oil	Sunflower Oil	Fat	36.630 (Hossain and Davies)	-
Deccan Hemp Oil	Sunflower Oil	Fat	32.787 (Hossain and Davies)	India, China, Pakistan (Khan, 2018)
Canola Oil	Sunflower Oil	Fat	10.000 (Hossain and Davies)	Canada, Western Europe (OEC, 2017)
Soy Protein	-	Protein	10.168 (Purdy and Langemeier, 2018)	-
Pea Protein	Soy Protein & Potato Protein	Protein	12.598 (South Africa Department of Agriculture & Rural Development, n.d.)	North America, China, Eastern Europe (FAO Stat, 2018)
Wheat Protein	Soy Protein & Potato Protein	Protein	17.132 (Purdy and Langemeier, 2018)	-
Potato Protein	-	Protein	18.372 (FAO, n.d.)	-
Mycoprotein (applied as a small percentage for whole cuts)	Soy Protein & Potato Protein	Protein	1.7 (Finnegan et al., 2017)	-

Appendix B: GIS Modelling Process

To quantify the agricultural area suitable for growing coconut in the top sourcing regions, relevant GIS data layers were first obtained and prepared for analysis. First, detailed country boundary layers were obtained from DIVA-GIS and projected into equal area projections to preserve land area (DIVA GIS, n.d.). Global Food Security-Support Analysis Data at 30 meters (GFSAD) was used to quantify current agricultural land area (Gumma et al., 2017, Oliphant et al., 2017, Zhong et al., 2017). The dataset, produced by NASA and made available by the United States Geological Survey, consists of large tiles of 30-meter resolution raster data indicating agricultural extents. Tiles covering the countries analyzed in this study were downloaded and prepared for analysis. The tiles were first merged for each country using the *mosaic to new raster* tool. Subsequently, they were projected into the same equal area projections as the country boundaries, and then resampled to one-kilometer resolution to enable analysis of large land extents. Raster values were then reassigned to a binary where agricultural area was assigned the value of one and non-agricultural land and water were assigned zero. Lastly, biome global data was obtained from The Nature Conservancy ecoregion dataset (The Nature Conservancy, n.d.). Individual ecoregion features were dissolved by ecoregion type, projected into the appropriate equal area projected, and converted to a raster with the same resolution and alignment as the one-kilometer agricultural data.

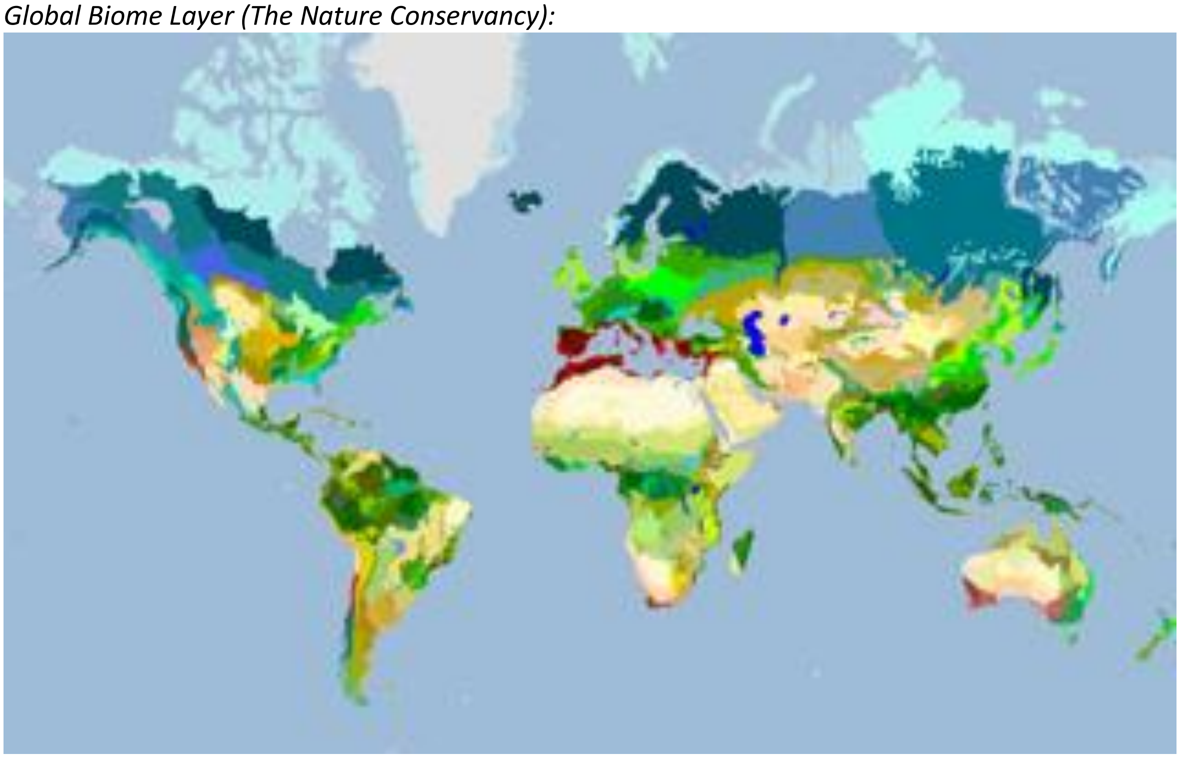
The tropical broadleaf moist forest ecoregion was identified as the most suitable biome for coconut production based on the location of top growing regions for coconut as well as necessary growing conditions. The ecoregion raster layer was reclassified as a binary, with tropical broadleaf moist forest designated as one, and all other ecoregions as zero. The raster calculator was then used to multiply the two binary layers together to produce a third binary layer with one assigned to areas that are both agricultural and in the appropriate biome, and zero encompassing all non-agricultural land and agricultural land in the incorrect biome. From this point, the *zonal statistics as a table* tool was used to calculate percentages of various land types within a specific country. For example, the agricultural land area appropriate for coconut cultivation within the Philippines was calculated using the sum statistic produced when adding all cells with a value of one in the third composite raster created within the Philippines boundary. These figures are stated in square kilometers and were converted to hectares. Relevant land areas were calculated and used for contextualizing Stella model projections for land area required for production and to inform the coconut oil case study.

Global Agricultural Land layer (NASA and USGS):



Source: https://landsat.gsfc.nasa.gov/new-landsat-based-map-of-worldwide-croplands-supports-food-and-water-security/

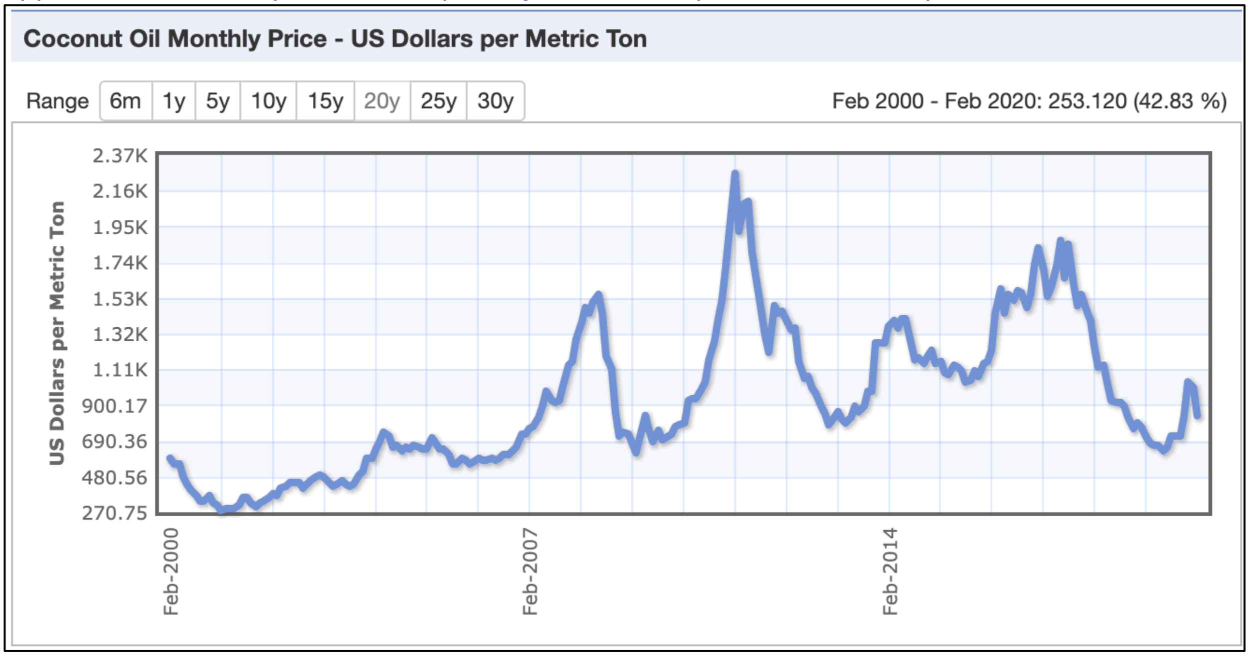
Global Biome Layer (The Nature Conservancy):



Source: The Nature Conservancy

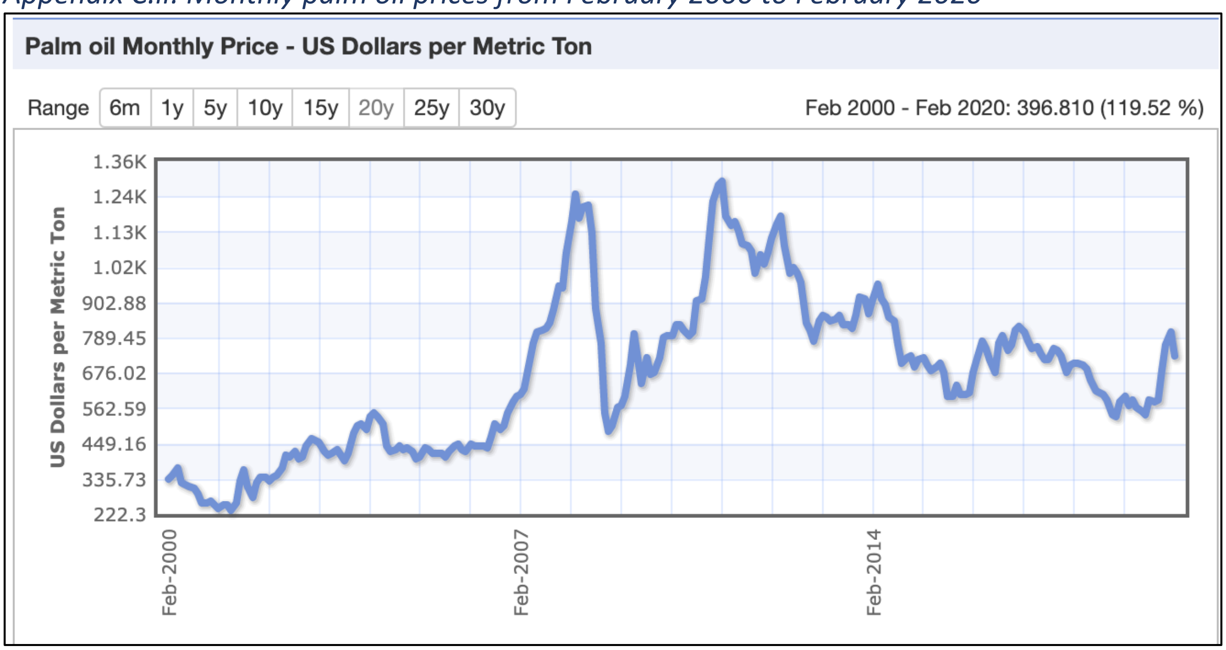
Appendix C: Economic Considerations

Appendix C.i: Monthly coconut oil prices from February 2000 to February 2020



Source: Index Mundi – Coconut Oil

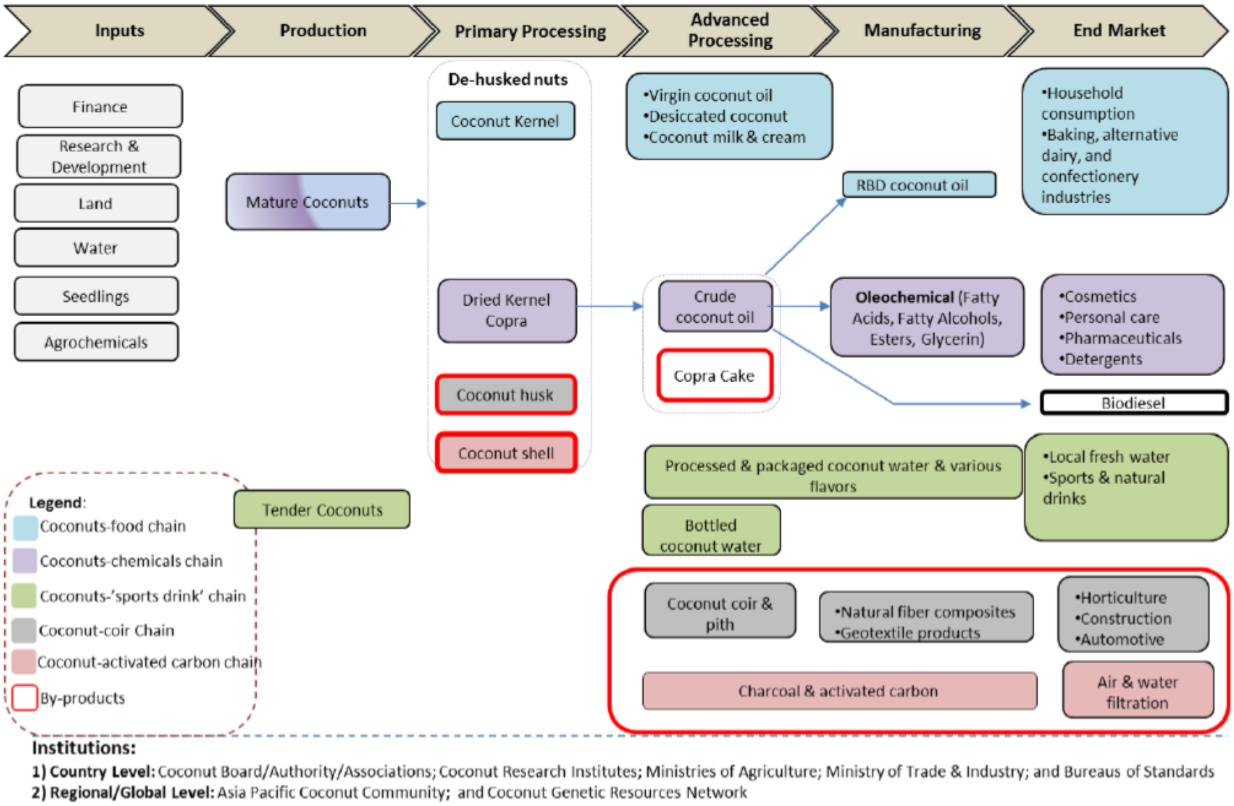
Appendix C.ii: Monthly palm oil prices from February 2000 to February 2020



Source: Index Mundi – Palm oil

Appendix D: Social Factors

Coconut Value Chain: input-output structure



Source: Abdulsamad, 2016

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