Using Food Waste to Reduce Food Waste

Evaluating the Impacts of Sourcing Food Waste as a Raw Material for Production

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UNIVERSITY OF CALIFORNIA Santa Barbara

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As authors of this Group Project report, we archive this report on the Bren School's website such that the results of our research are available. Our signatures on the document signify our joint responsibility to fulfill the archiving standards set by the Bren School of Environmental Science & Management.

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The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

Dr. Kelsey Jack

Date

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Abstract

The concept of "circular economy" has recently gained traction as a way to help companies become more sustainable. Circular economy suggests that environmental impacts can be reduced by sourcing wastes rather than virgin materials. However, this claim remains largely untested. This project works with Apeel Sciences, a small biotechnology startup interested in sourcing food waste as an input to their product, to evaluate the environmental impacts of sourcing waste using two different Life Cycle Assessment methodologies, economic allocation and substitution. We show that economic allocation may not capture impacts outside the immediate system of interest, which we demonstrate can be as large if not larger than those generated by the immediate system. This is particularly true when the "waste" under consideration is not truly a waste and has another established use. Therefore, using different methodologies results in different recommendations of what to source based on environmental impacts, highlighting that sourcing wastes may not be as sustainable as originally thought. We distill these findings into a comprehensive framework that allows companies to replicate our analysis and develop a more holistic understanding of the environmental impacts of sourcing a waste.

Executive Summary

Introduction and Significance

As natural resources become more limited and consumers increasingly demand sustainable products, companies are looking for ways to make their supply chains less environmentally harmful. One concept that has gained traction in recent years is to source wastes from a product system as primary inputs to a different product system. Commonly referred to as "circular economy," it suggests that sourcing wastes rather than virgin materials can mitigate the negative environmental impacts associated with a company's production processes by avoiding the impacts of extraction.

While the idea of circular economy has been quick to catch on within the business community, there have not been many scientific analyses done to validate its claims (Korhonen et al., 2016; Zink & Geyer, 2017). To avoid a scenario in which a shift to a "circular" supply chain results in higher net environmental impacts, organizations must be able to quantitatively evaluate potential systems that use waste as inputs.

Life Cycle Assessment (LCA) is a tool that is traditionally used to calculate the environmental impacts of product systems. There exist multiple LCA methodologies, broadly falling into two main categories: allocation and systems expansion. The International Organization for Standardization has developed a hierarchy of methods that favors systems expansion over allocation, however producing organizations are not always able to evaluate their products to that extent due to limited time and data availability

This project works with Apeel Sciences, a company interested in taking a circular-economy-like approach to their supply chain, as a case study to assess how current LCA methodologies and available data can be used to analyze the impacts of sourcing a waste. Apeel is interested in sourcing food wastes that occur at the industrial level as a primary input to their production process. Through this analysis, we provide a framework that organizations can use to critically assess opportunities to create circular supply chains.

Objectives

Through our case study with Apeel Sciences (Apeel), we sought to develop a framework to evaluate the environmental impacts associated with sourcing a waste as an input to production.

The primary projects objectives were to:

1. Understand how a particular waste is created and how it is ultimately used/disposed of
2. Understand how differing LCA methodologies available to organizations might affect sourcing decisions
3. Identify the characteristics of certain scenarios that may cause a sourcing decision to be more or less environmentally harmful

To accomplish these objectives, we answered the following research questions for possible sourcing scenarios for Apeel:

1. What is the life cycle of a feedstock derived from waste?
2. What are the environmental impacts of each feedstock, and how do the results change with different LCA methodology approaches?
3. What characteristics of sourcing scenarios make them more or less environmentally harmful?

Methods

Research Question 1: What is the life cycle of a feedstock derived from waste?

Through literature review, we developed detailed profiles for the feedstocks under consideration. The profiles covered how the feedstock was produced, what processes occurred before the feedstock was separated from the primary product (referred to as the separation point) and what other industries or products might be able to use this feedstock. From this research we designed specific hypothetical scenarios for our quantitative analysis, based on data availability as well as what we considered to be the most likely situation to occur. These profiles also helped us generate initial screening questions that an organization should consider when deciding to source a waste.

Research Question 2: What are the environmental impacts of each feedstock, and how do the results change with different LCA methodology approaches?

To quantify and compare the environmental impacts of each selected feedstock, we used two different LCA methodologies: economic allocation and substitution, which can be thought of as a paired down version of the systems expansion methodology. Under most circumstances, a company would likely need to adopt a shortened version of systems expansion in order to perform the analyses in a timely manner due to the heavy data requirements. We gathered quantitative data from past LCAs of the primary product that the waste feedstock would be generated alongside. We then calculated how each methodology would assign impacts to the waste. For both methodologies, we quantified four impacts using the IMPACT 2002+ method (Jolliet et al., 2013): global warming potential (kg-CO^2 eq.), acidification potential (kg-SO^2 eq.), eutrophication potential (kg-PO^4 eq), and land occupation (m^2 of arable land). To calculate the impacts using economic allocation, we partitioned averaged the impacts generated from any processes upstream the separation point using a price ratio.

The substitution method considers the effect of diverting the waste feedstock from a possible alternative use and adds the additional burden of replacing the feedstock with another material to the overall impact of sourcing the feedstock. An example might be a situation where the waste is composted and then used as fertilizer on the farm. If that waste were removed, the replacement material might be chemical fertilizer. To do this, we had to determine how much of the replacement material would be needed to fulfill the same function as the feedstock. This created a “substitution ratio” and determined the magnitude of impacts that should be associated with the waste feedstock if it were diverted from this use by Apeel.

Research Question 3: What characteristics of sourcing scenarios make them more or less environmentally harmful?

After computing our baseline results, we wanted to understand how the results might change with changes in the specific scenario. We explored this by manipulating the key parameters in each analysis. For economic allocation, we calculated impacts by using both a higher and lower price ratio than the baseline based on historical values of the primary product. For the substitution methodology, the main parameter was the substitution ratio, which was increased by 10% and decreased by 10% compared to baseline.

Lastly, we also wanted to understand how including additional processes might affect the results for both economic and substitution. For this we added a dehydration process. Since each feedstock had a different water content, the amount of heat needed to dehydrate varied across feedstocks. By adding the additional impacts of generating this heat, we were able to examine how this might change the baseline results.

Results

Our results include detailed profiles for four selected feedstocks: olive pomace, coffee cherries, grape pomace and cocoa husks. A key finding at this stage was that all of the feedstocks could be useful in other industries in some capacity, and therefore would be considered “by-products” rather than “waste” depending on the specific scenario.

Our quantitative analysis revealed differences in which feedstock would be considered the least impactful, both across the two different methodologies and across the four impact categories. For all four impact categories, the feedstock with the lowest impact differed depending on whether economic or substitution allocation was used. Cocoa husks were the least impactful across all four feedstocks if using the substitution method but were only the least impactful in terms of land occupation if using the economic method.

Lastly, our scenario analysis tested whether changing the assumptions made in our baseline scenarios might help differentiate the feedstocks. Manipulating the price across the different feedstocks did change which feedstock had the lowest impacts in each category but did not reveal one feedstock that always had the lowest impacts.

Conclusions

Overall, our analysis did not reveal a single feedstock to be less impactful than the rest as different LCA methodologies generated different results. However, from these results we were able to build a framework that a company can use to help consider whether sourcing a waste or byproduct from another system as an input to production can actually help lower its environmental footprint. In approaching this type of decision, we highlight 4 main conclusions:

1. **Even things that are generally regarded as waste may have an alternative use.** It is important that organizations conduct adequate due diligence, to ensure that a waste is indeed a waste.

2. **Choice of methodology by the analyst affects the decision outcome**. A feedstock may not inherently be more environmentally friendly, it may be a product of the methodology and specific scenario the analyst is choosing.

Based on our results, we recommend organizations and/or analysts approaching a similar question always do the following

3. **Set specific environmental goals.** The feedstock with the lowest environmental impacts differed across impact categories for both methodologies. It is therefore crucial for companies to approach a sourcing decision with specific goals and objectives in mind. These could relate to larger social or environmental issues the company values, or that are part of an overall strategy.
4. **Identify specific potential sources in addition to specific feedstocks.** Within the economic allocation methodology, changes in market prices for primary products result in several feedstocks having overlapping impact ranges.

Overall, we find that organizations need to approach a circular sourcing decision holistically to avoid shifting environmental burdens to another system. We distill these findings into a comprehensive framework that allows companies to replicate our analysis and develop a more holistic understanding of the environmental impacts of sourcing a waste.

Project significance

The manufacturing of products that we use on a daily basis places an enormous strain on the environment. The life cycle of most man-made products involves the extraction of natural resources, processing to assemble and finish the product, a use phase where it provides a service, and finally a disposal phase. This structure is known as a linear product system, and often results in physical damage to natural ecosystems, strain on natural resources, and pollution.

Two major shifts are helping to change how some organizations design their production systems. As natural resources become limited and consumers increasingly demand sustainable products, companies are looking for ways to make their supply chains less environmentally harmful. One concept that has gained traction in recent years is sourcing wastes from one product system as primary inputs to different product systems, commonly referred to as “circular economy.” This concept has become popular among sustainability-minded firms, as it suggests that sourcing wastes rather than virgin materials can mitigate the negative environmental impacts associated with a company’s production processes, mainly by avoiding the impacts of extraction and disposal.

However, to validate these claims, the environmental impacts associated with a circular supply chain must be quantified. Life Cycle Assessment (LCA) is a tool traditionally used to calculate the environmental impacts of product systems. Unfortunately, when it comes to using wastes, conventional LCA methodology may not fully capture the resulting impacts.

This project works with Apeel Sciences, a company interested in taking a circular-economy approach to their supply chain, as a case study to assess how current LCA methodologies can be used to analyze the impacts of sourcing a waste as compared to a virgin material alternative. Apeel is interested in sourcing food wastes that occur at the industrial level as primary inputs to their production process. This project aims to help Apeel and other companies consider how sourcing wastes may have additional environmental burdens beyond what has traditionally been calculated.

Background

For most of the 20th century, economic policy has largely disregarded environmental concerns, instead promoting maximum growth of production (Arrow et al., 1995). Operating under general belief that as countries prospered, they would eventually take action to protect the environment, institutions and policymakers often favored production rather than environmental regulation in the short term (Arrow, 1995; Dinda, 2004).

The consequences of this largely unconstrained growth in production are clear today. The magnitude of the impact on Earth is considerable and cannot be ignored. It is scientifically recognized that humanity is approaching or even exceeding critical thresholds of what our biosphere can sustain, putting ecological systems at risk of breaking down or shifting into new states (Rockstrom et al, 2009; Steffen et al. 2015).

In response, policymakers now increasingly seek ways to reign in the impacts of production on the environment. As institutional barriers often make it difficult to influence government driven regulation at the global scale, producing organizations themselves can be potentially more effective and generate positive business outcomes by taking the initiative to create more sustainable supply chains.

1. Circular Economy

A supply chain refers to all the linked processes involved in sourcing materials for the creation and assemblage of a product. One potential way to increase the sustainability of supply chains is to source waste materials rather than virgin materials extracted from natural resources.

Utilizing wastes to create new products is not a novel concept; the practice was formally recognized in 1960 and was incorporated into various industries' strategies by 1980 (Zink & Geyer, 2017; Frosch & Gallopoulos, 1989). The concept has recently been re-coined: "circular economy" (CE), and has been embraced by many businesses as a way to become more environmentally friendly (Ellen MacArthur Foundation, 2015). CE is a concept that has been popularized within the business community because it broadly outlines a way for companies to decrease their environmental footprints by using wastes and by-products rather than harvesting or extracting resources from the environment. While it lacks a standard definition, the concept is underpinned by a number of broad principles (Ellen MacArthur Foundation, 2017):

1. "Design Out" waste and pollution - products should be designed in such a way minimizes waste and pollution
2. Keep products and materials in use
3. Regenerate natural systems

Of these principles, the most pertinent to our project is that of keeping products and materials in use. CE identifies a need to change the way in which resources are consumed in order to fit within natural systems. The change takes the form of using resources in a more "circular" way as compared to the linear product system. Here, "linear" refers to the manner by which a resource is extracted, production, used and landfilled, whereas "circular" refers to the model by which a resource is extracted, used, and diverted for continued use. (Ellen MacArthur Foundation, 2017) (Figure 1). The circular model (also known as "closed loop") aims to repurpose resources continuously for other means (i.e. to be maintained, reused, refurbished etc.), and then to ultimately break it down into raw materials to create an entirely new product.

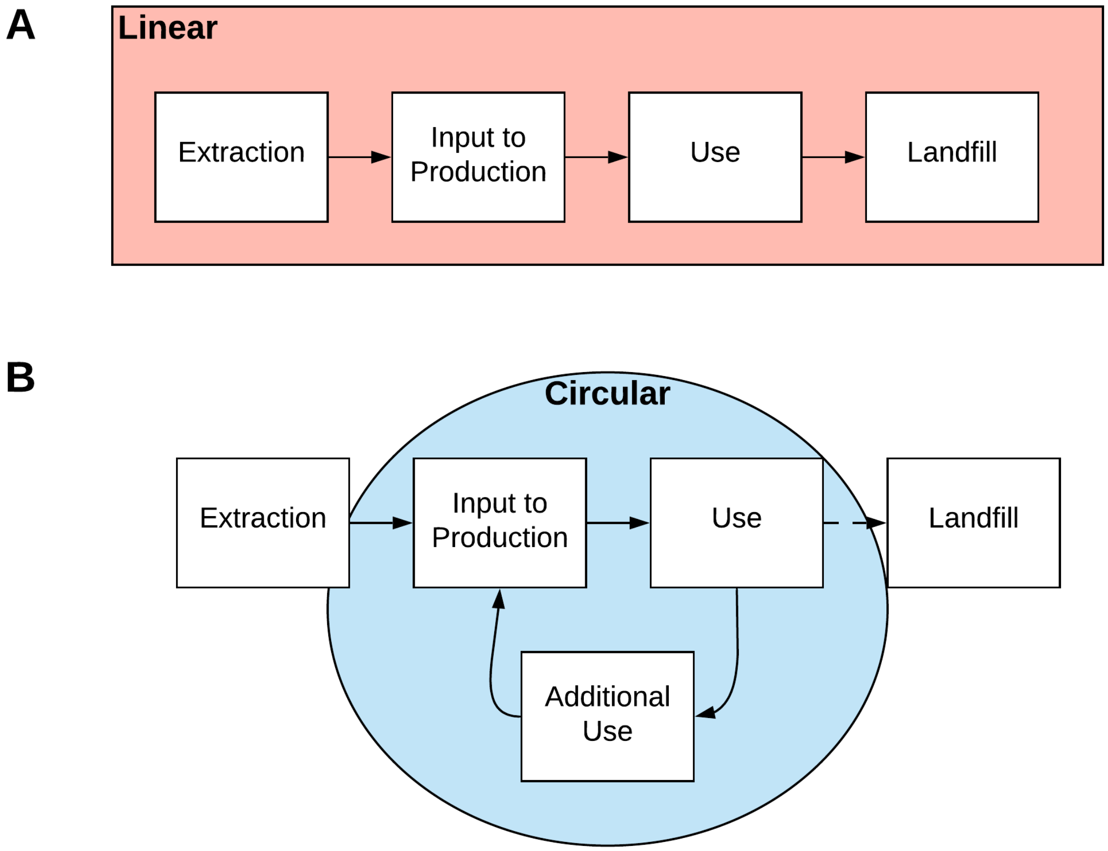

Figure 1. Comparison between linear and circular production systems. In linear product systems (A), resources are extracted for production of a product, the product is used, and ultimately discarded once it has seen its useful lifespan. In circular systems (B) use components of the made product or the entire product itself as inputs to the production process, therefore mitigating or eliminating the need for both extraction of new resources and landfilling.

Recent case studies by Genovese et al., (2017) assessing the effectiveness of "closed-loop" interventions indicate that shifting to a circular supply chain can help companies reduce their carbon emissions, when compared to the more traditional linear supply chain. However, a key aspect common across these case studies is that the waste product that is reused as an input to the main product is otherwise assumed to be discarded. Therefore, the reduction in carbon emissions generated by reconfiguring the supply chain is mainly driven by the replacement of virgin input material with waste (Genovese et al., 2017).

Evidence that replacing virgin material with waste will result in a more sustainable supply chain highlights the need to carefully consider what practitioners define as waste. Without this type of scrutiny, a firm or organization risks shifting environmental burdens to another part of the system, or another system entirely. The potential for circular supply chains to result in this type of problem displacement suggests that a firm's decision to implement circular economy practices must be assessed in terms of its net environmental impact on the biosphere (Zink & Geyer, 2017). However, there exist limitations in methodologies available to undertake this kind of broad assessment of the net environmental impact of sourcing a waste (Korhonen et al., 2016; Zink & Geyer, 2017).

2. Life Cycle Assessment - Current Methodologies

A common tool used to assess the environmental impact of production is life cycle assessment (LCA). LCA quantifies the environmental impacts of a product system through a specified length of the product's lifecycle. Within a single process, a waste product or by-product may be produced alongside the primary product. This creates a scenario where multiple products are generated from a single system. In this case, it is difficult to isolate the environmental impacts of just one of the products created. This issue is a commonly debated point within the LCA community (Weidema, 2000; Tillman, 2000; Ayer et al., 2007; Mackenzie et al., 2017). Generally speaking, this issue is addressed with the application of different LCA methodologies: allocation or systems expansion.

2.1 Allocation

Allocation "is a process of partitioning the input and output flows to the product system under study" (Lee and Inaba, 2004). Allocation splits a system's impacts between all products. The split compares the multiple products created from one supply chain based on a criterion such as economic value, energy content, or mass (Wardenaar et al., 2012; Ardente & Cellura, 2012). The choice of criterion reflects an underlying assumption. When using mass-based allocation, the assumption is that the environmental impacts incurred are a consequence of the amount of materials used. Alternatively, economic allocation assumes that the impacts are a consequence of the value derived from the system (i.e. if the system had no value, its production would cease).

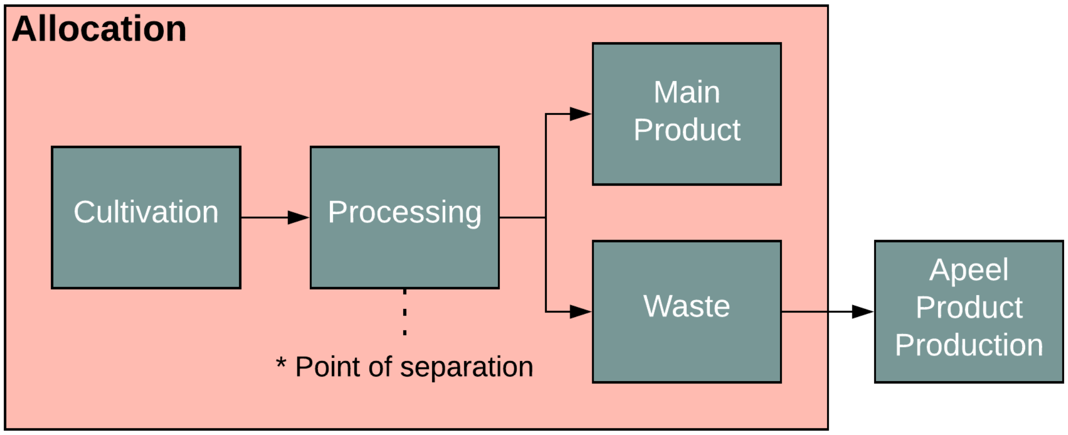

Figure 2. Illustration of how impacts are partitioned to waste using allocation. The pink box represents a boundary outlining the processes and subsequent products that generate environmental impacts. Allocation divides the impacts of any process occurring before the point of separation among the two outputs, the main product and the waste.

2.2 Systems Expansion

The systems expansion LCA methodology compares product systems based on identical outputs (Weidema, 2000). For example, the supply chain that produces the corn bought in supermarkets can also produce ethanol. If we wanted to compare the environmental impacts of producing corn ethanol with regular gasoline using systems expansion, we would have to compare the impacts of the corn ethanol supply chain with the impacts from both the gasoline supply chain, in addition to a supply chain that produces corn. In other words, systems expansion seeks to add or subtract impacts of additional processes to a system so that systems can be compared based on identical outputs.

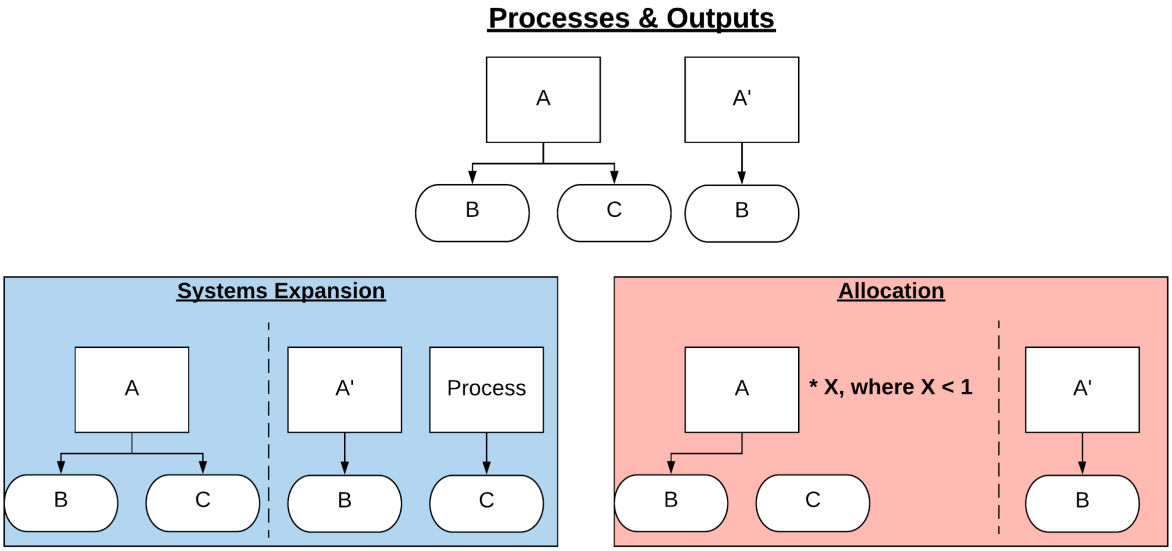

Figure 3. Comparison between allocation and systems expansion LCA methodology. If assessing two different systems that produce the same product (B), system expansion compares process A vs A' plus an additional process which only produces output C. This creates a comparison between two systems with identical outputs B and C. Allocation takes a fraction of system A so that it theoretically only produces output B against A'. In allocation the systems are compared against only producing output B.

According to the International Organization for Standardization (ISO) standards, practitioners should try to use systems expansion before resorting to allocation, however in the event that allocation is utilized, the partitioning should be done based on the following hierarchy (Lee and Inaba, 2004):

1. Use physical relationships between the inputs and outputs of a unit process
2. Use the economic values or physical quantities between the multiple products.

Despite the stated preference towards system expansion, allocation (particularly allocation by economic value) remains a prevalent practice among producing organizations (Mackenzie et al., 2017; Wardenaar et al., 2012; Notarnicola et al., 2015). This practice can be problematic, as the results of LCAs are often sensitive to the selected method, this is particularly true in the case of wastes (Luo et al., 2009; Wardenaar et al., 2012; Huang et al., 2013). The different results produced by different methodologies may be consequential if a company selects what to source based on environmental impact; they may end up arriving at different choices.

Both systems expansion and allocation have considerable limitations in terms of their ability to assess the net environmental impact of a firms' decision to source. While systems expansion presents a framework to include products and processes beyond that of one individual firm, it is extremely data burdensome. However, the narrow scope of the allocation method makes it difficult to encompass effects of a sourcing decision beyond a singular production system and market. Ideally, a company would want to understand both the impacts of the immediate system of interest, as well as the potential effects on other product systems their sourcing decision might have if they truly want to improve environmental outcomes of their own supply chain.

3. Case Study: Apeel Sciences

This project aims to assess the differences in LCA methodology when considering wastes as an input for production through a case study with Apeel Sciences (Apeel). Apeel was established in 2012 with the goal of reducing food waste in the produce supply chain. Their product is a plant-derived, edible coating that can be applied to fruits and vegetables to slow the ripening process, thereby extending the shelf life and preventing spoilage. A longer shelf life for produce has the potential to add value and reduce waste at essentially every part of the produce supply chain.

Apeel strives to be as sustainable as possible in all aspects of their company operations. They have gone so far as conducting a complete (cradle-to-grave) life cycle assessment of their product on different produce types (Vieira, 2020). Apeel is in the unusual situation of creating environmental benefits through the use of their product (i.e. on average, fewer environmental impacts occur from produce treated with Apeel's product than without). Within their LCA, they pay particular attention to the idea of capturing the environmental benefits their product enables. This means that Apeel needs to minimize the impact of creating their product. One way of doing so could be by sourcing less impactful input materials. In line with CE thinking, a proposed idea to increase sustainability in the manufacturing of their edible coating is to use food waste as an input to the process. Fruit and vegetable peels, seeds, and pulp are all components of a plant that could be used to create Apeel's coating. Apeel is interested in understanding the environmental impacts of different food waste options in order to make a sourcing decision that will further minimize the environmental footprint of their product's supply chain.

In Apeel's case, the wastes in question are industrial agricultural wastes. These are wastes consisting of organic material generated through processing crops or creating food products. Wastes occurring on an industrial level tend to be mostly uniform and are able to provide an appropriate volume of material, as compared to organic waste occurring post-consumer. Industrial agricultural wastes can be problematic from an environmental standpoint as the large magnitude of material can also have large scale environmental impacts when disposed of. In 2011, food waste generated at the cultivation stage worldwide was responsible for an estimated 2.2 Gt of CO_2e (Porter et al., 2016). Furthermore, loss of product at the industrial level represents a significant source of inefficiency, causing producers to increase land use and inputs needed to generate a given harvest. Therefore, finding ways to use this waste creates a potential opportunity for Apeel and the agricultural or food producers to mutually benefit, lowering Apeel's environmental impact and increasing agricultural and food production efficiency.

Apeel wants to understand net impacts of sourcing a waste, enabling them to make an informed and sustainable decision. By assessing the ability of existing LCA methodologies to quantify environmental impacts of waste, we highlight the challenges companies may face when attempting this kind of analysis and present an improved decision framework and calculation tool that accounts for effects felt beyond a single organization's supply chain.

Project Objectives

In order to provide Apeel with an approach to evaluate sourcing waste as an input to their production, our project aims to answer the following questions:

1. What is the life cycle of a feedstock derived from waste?
2. What are the impacts of each feedstock, and how do the results change with different LCA methodology approaches?
3. What characteristics of sourcing scenarios make them more or less environmentally harmful?

In answering these questions, we provide a framework and tool that any organization can use to assess whether transitioning to a circular supply chain will help reduce their net impact on the environment. The tool will guide users through our assessment of both a product's impacts as calculated by traditional LCA methodology (economic allocation) and through our proposed methodology, which assesses the impacts that sourcing a waste can cause if the waste is already being utilized in some way.

Underlying this analysis were two key assumptions:

- **Partial Equilibrium** – We assume prices for the wastes and primary products are not changing in response to a decision to source a feedstock. Similarly, production within the system is not changing in response to additional revenue generated from the newly sourced waste.
- **Scope of Comparison** – We assume potential feedstocks are compared to one another, without comparing to what Apeel is currently sourcing as inputs. Therefore, this paper will not comment on whether sourcing a waste will lower Apeel's environmental footprint in comparison to their current sourcing scenario, rather we will comment on which of the proposed options is best relative to one another.

We assumed partial equilibrium so as to isolate the impacts considered in our analysis to the current system, rather than a predicted future state system that might arise due to changes in production. This helped us manage our scope, and we believe that organizations might do the same to keep their analyses feasible.

For the privacy of Apeel's intellectual property we limited the scope of comparison to only consider processes outside their current operations.

Methodology

We answered our research questions in three main steps:

1. Identify feedstocks and develop feedstock profiles
2. Derive environmental impacts associated with each feedstock
3. Conduct a scenario analysis to determine what characteristics of a particular sourcing option may increase or decrease the environmental impacts

1. Identify feedstocks and develop feedstock profiles

1.1 Selection method

Apeel provided a list of feedstocks, all of which had the desired chemical composition to function as inputs to their product. From this list, we first designed criteria to choose a subset for full analysis. The goal was to select four feedstocks that best represented general categories of the provided options and would therefore help generate broad conclusions about what characteristics of a given feedstock (and its sourcing scenario) might affect its environmental impact.

The initial step in doing so was to divide the full list into groups based on similar characteristics. Based on initial research provided by Apeel, all feedstocks were either sorted into a "waste" or "by-product" group. The categorization of each feedstock as a waste or a by-product at this stage was only procedural, as further research into selected feedstocks would later reveal almost all can be considered by-products. These two groups were further sorted into four distinct subgroups based on similarities in physical characteristics or attributes.

Next, we needed to select one feedstock from each of the four subgroups. The criteria for analysis fell into two main categories: sourcing feasibility and data availability. Considerations to determine sourcing feasibility included prevalence of the feedstock, supply chain characteristics, and what other industries might use the feedstock as an input. Data availability considered the number of existing credible sources that described a specific feedstocks' supply chain, and/or how transparent related industries were in their information.

For example, while papaya seeds are a potential feedstock that could be used to create Apeel's product, initial research revealed that papaya seeds contain biologically active compounds that are valuable to the pharmaceutical industry (Boshra, 2013). Because intellectual property is one of the key assets retained by pharmaceutical companies, it is difficult to obtain transparent information on how specific substances are used in pharmaceutical products and what transformations they might undergo. This information is key to completing the project analysis, and therefore papaya seeds were ruled out due to lack of available data and transparency.

Another example is pumpkin seeds, where sourcing feasibility became a potential limitation. Illinois, Indiana, Texas, and California contribute to most of the country's pumpkin production (USDA ERS, 2019). Considering Apeel's location, pumpkins grown in California would be the most ideal option. However, the pumpkin species grown in California (Jack-O-Lantern) is mainly used for holiday decorations. Hence, they are directly sold to consumers after harvesting (Aegerter et al., 1997). This means that the pumpkin seeds would be sourced from the consumers, which is considerably harder than sourcing from farms or processors. Hence, pumpkin seeds were ruled out due to poor sourcing feasibility.

1.2 Research

As a next step, we gathered information on the supply chains that generated each waste or by-product. Given the diversity of information available it was also necessary to develop criteria at this stage to help shape information used, and assumptions made, for the quantitative analysis. The key questions asked, and the criteria used to answer them are as follows.

1) What is the primary product being made that generates this waste or by-product?

   Given multiple potential options, the most common primary product was prioritized. For example, grape pomace is a by-product from making both grape juice and wine, yet 60 - 80% of raw grapes are cultivated for wine in the main grape producing regions (Galankis, 2017). Therefore, for grape pomace we chose to analyze the wine supply chain.

2) What production system separates the by-product or waste from the primary product?

   Once a primary product has been selected there may be multiple different processes used to create that product. Olive oil and its by-product olive pomace can be processed using a traditional stone grinder or a highly mechanized centrifuge system. Because the impacts resulting from these two processes differ, we had to choose only one process to analyze for the initial results (Azbar et al., 2004). Given that traditional methods are rarely used, especially in globalized olive oil supply chains, the mechanized supply chain was used for the detailed analysis.

3) What processes or transformations occurred before the point of separation, and what inputs and outputs were generated?

   In order to use the allocation LCA methodology, we needed to account for any environmental impacts occurring upstream of the separation point (the point in the supply chain where the primary product is separated from the waste or by-product). Impacts upstream from the separation point would be partially allocated towards the waste or by-product, while any impacts downstream of the separation point would not be carried by the waste or by-product. For example, considering wine production, the upstream process includes viniculture, crushing, and pressing. Therefore, when using the allocation methodology, all impacts generated during these processes would be partly allocated to the grape pomace.

4) What processes or transformations occur after the point of separation?

Any input needed for, or outputs generated from, the primary product after the separation point would not be attributed to the waste or by-product. This was important to understand during the data collection process (described in more detail below) as different studies had varying scopes determining what parts of the product system were analyzed. Considering wine production again, impacts from the downstream processes of wine production such as transportation or bottling would not be allocated to the grape pomace.

5) What is a common fate of the waste or by-product?

Here we sought to determine if the feedstocks characterized as wastes were true wastes - that is, were disposed of after separation from the main product. We found possible uses for all four feedstocks other than landfill, characterizing them all as by-products depending on the specific scenario. For example, coffee cherries can be used as an input to other products, yet in many coffee producing regions they are more often discarded into the environment (Kassa et al., 2014). To model how different fates of a particular feedstock may influence the quantification of environmental impacts, we considered a situation where coffee cherries were being used as cattle feed. We chose this scenario as it has been evaluated quantitatively in the literature and represents a use that could help a high impact industry (meat production) become more environmentally sustainable (see Results 1.2).

2. Derive impacts

Lacking primary data, we used existing life cycle impact assessments (LCIA) from the literature to derive the impacts for each feedstock. To maintain consistency, the literature was evaluated within the following framework. Through consultation with Apeel we believe that this analysis closely resembles what businesses would likely do in practice, as they often do not have primary data for a potential sourcing change.

2.1 Goal

The goal of the quantitative analysis was to compare results from using two different LCA methodologies to evaluate impacts of sourcing waste feedstocks. We calculated impact results using economic allocation, as well as a substitution method that illustrates an approach similar to systems expansion.

2.2 Scope

1. Functional Unit: Value to Apeel

For our baseline results, we consider all feedstocks to have the same capacity of service to Apeel. Therefore, we derived impacts for 1 kg of dried feedstock for all four options. We assume that the feedstock would be delivered to Apeel in its most functional form.

2. System boundary - Allocation

The system boundary determines what processes of a product supply chain are and are not included when calculating the environmental impacts. Deriving the impacts for the feedstocks using an economic allocation methodology included all processes before the separation point. For all feedstocks, this includes cultivation, some initial processing that occurs either on farm or at a processing facility, and then some mechanical process to separate the feedstock from the material that will be used to create the primary product. Also included is transportation between any of those processes. This system boundary accounts for the environmental impacts of the production of the feedstock and its corresponding primary product.

3. System boundary - Substitution

For the substitution methodology, the system boundary differed in that instead of including all processes upstream of the separation point, it included impacts that would result from diverting the waste from its original use. This way of viewing the product system is more in line with the systems expansion LCA methodology in that it includes processes that are not tied directly to the production of the waste, but that

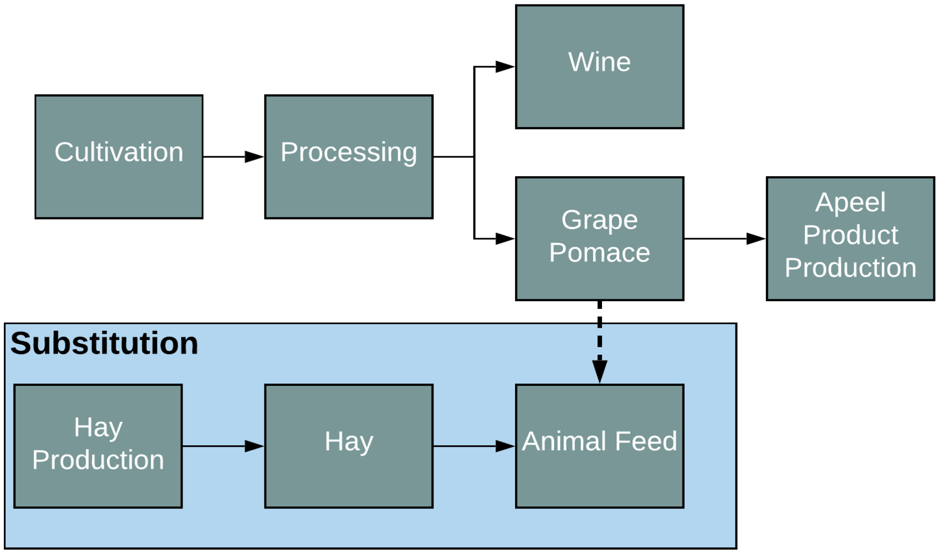

Figure 4. Illustration of how the substitution methodology quantifies the impacts of sourcing a waste feedstock. Black arrows indicate material flows. Grape pomace that was originally used as animal feed is diverted to Apeel. To replace the pomace, hay is now sourced as animal feed. Because Apeel made the decision which diverted the grape pomace, the impacts of the additional hay production are assigned to Apeel.

still could be affected by a change in the waste's fate. Using this methodology, we consider the scenarios where that the feedstock has a use in another industry. When Apeel diverts some amount of feedstock, we assume that the gap in material this diversion causes for the original user will be filled or substituted with some other input. Therefore, any impacts from the material that must be substituted for the displaced feedstock would be assigned to the feedstock when used by Apeel. This way of drawing the system boundary differs from allocation where instead of quantifying impacts of the processes that create the feedstock (upstream of the separation point), we attempt to quantify the environmental impacts that Apeel's sourcing decisions could have on other systems. The schematic below illustrates this example for grape pomace.

4. Excluded from system boundaries

Excluded from the boundaries of both methodologies are any processes that occur once the feedstock has reached Apeel. Furthermore, our system boundary does not consider use phase or end-of-life for the feedstocks or the alternative uses.

5. Excluded due to cut off criteria

Due to lack of available data we are not able to include transformational processes that may be used to treat any of the feedstocks to prepare them for their alternative use, or for transport to Apeel. Additionally, the transportation to Apeel specifically is excluded as specific information on where a feedstock is located and the means by which it would travel to Apeel are unknown. Despite not including these processes, we do model how the inclusion of additional processes can impact the overall results (see 3.1.3 *Dehydration and transportation* below).

3.3 Calculation of impacts

Below we outline the specific equations we used to calculate the environmental impacts of each waste feedstock. These equations are also incorporated into our tool so that users can replicate the analysis.

Economic allocation

Economic allocation was used for the first methodology. A price ratio was calculated between the primary product and the feedstock, which was then used to partition the impacts from the processes included in the system boundary. For three feedstocks, there was no readily available price data - this is because while there exist uses for these feedstocks (i.e. compost for organic fertilizer), there still do not exist established large-scale markets for these materials. In these cases, a hypothetical price was estimated by considering the opportunity cost of the material. For example, in a scenario where grape pomace could be used as animal feed, the price of material that would serve the same function (i.e. hay), would be used as the opportunity cost price for grape pomace. The exception was if there was existing market and price data available, which was true for one of the four feedstocks. Specifically:

With a unit amount of waste m_w, the amount of primary product is

$$\boldsymbol{m_p = m_w / r_w}$$

where r_w is the primary product to waste ratio.

Then, the allocation ratio of impacts for waste is calculated as

$$\boldsymbol{r_a = m_w p_w / (m_w p_w + m_p p_p),}$$

where p_w and p_p are unit prices for waste and primary products respectively.

Hence, for each studied impact i (in this project, i includes global warming potential, acidification potential, eutrophication potential, and arable land occupation), the amount allocated to the waste is

$$\boldsymbol{I_{wi} = r_a I_{pi}}$$

where I_{pi} is the amount of impact produced by the primary production system generating primary product m_p and waste m_w. Note that I_{pi} is normalized from values extracted from existing literature based on the corresponding functional unit.

Substitution

The substitution method was employed as our second methodology. This method considers the effect of diverting the "waste" feedstock from a possible alternative use and assigns the burden of replacing the feedstock with another material to the impact of sourcing the feedstock. For example, if Apeel were to choose to source grape pomace from a producer who normally sells or uses the pomace as animal feed, the animal feed producer may instead turn to source another material that provides the same service the grape pomace did, such as hay. The amount that would be substituted was calculated based on the function that the grape pomace and the hay would serve. In the example of grape pomace as animal feed the service was to provide caloric content. Therefore, the amount of hay being substituted would be based on the caloric equivalency between hay and grape pomace. The burden of the hay equivalent of 1 kg of grape pomace would be the impact of grape pomace as an input to Apeel. Specifically:

With a unit amount of waste m_w, the amount of substitution product is

$$\boldsymbol{m_s = m_w r_s,}$$

where r_s is the substitution/backfill ratio.

For each studied impact i, the amount generated by the substitution production system is

$$I_{si} = m_s i_{si},$$

where i_{si} is the unit impact produced by the substitution system extracted from the EcoInvent dataset.

We calculated the impacts using this substitution scenario twice, once using a substitution product that was differed for each individual feedstock, and again for a substitution product that was common across all four feedstocks. We selected the specific products based on the research we conducted as part of our first objective (1.1).

2.4 Life cycle impact assessment

The environmental impacts from the feedstocks were evaluated using the IMAPCT 2002 + method. IMPACT 2002+ consists of 14 categories of environmental effects that result from elementary flows included in the analysis (Jolliet et al., 2013). These categories can then be aggregated into 4 overarching damage categories. For the purposes of this project, we report results for four categories: global warming potential, aquatic acidification potential, eutrophication potential, and land occupation (Table 1). These four categories were selected as they were consistent across previous LCIA analyses using the IMPACT 2002 + for all four feedstocks. For a more detailed discussion LCIA methods employed please see Appendix A.

Table 1. Impact category, units of measurement, definition and effect of the four impact categories selected for this analysis. Each impact contributes to processes that can result in the environmental degradation listed under the potential damages column.

Impact Category	Unit of Measurement	Definition	Potential Damages
Global Warming Potential	kg CO_2 equivalent	Alteration of global temperature caused by greenhouse gas emissions released through human activity. The timescale in which the GWP is assessed in this study is a 100-year time horizon.	Crops, forests, coral reefs, etc. (biodiversity decreases in general). Temperature disturbances. Climatic phenomenon abnormalities.
Aquatic Acidification Potential (Acidification Potential)	kg SO_2 equivalent	Reduction of the pH (increase in acidity) in water systems due to the acidifying effects of anthropogenic emissions. Fertilizer use is a common contributor to aquatic acidification.	Damage to the quality of ecosystems and decrease in biodiversity.

Aquatic Eutrophication Potential (Eutrophication Potential)	kg PO_4 equivalent	Accumulation of nutrients in aquatic systems. Fertilizer is a common contributor to aquatic eutrophication.	Damage to the ecosystem quality.
Land Occupation (Land Use)	m^2 of arable land	Direct land used continuously for a certain human-controlled purpose, e.g. agriculture, forestry or buildings.	Impacts on the terrestrial ecosystem, biodiversity, resource availability and soil quality.

3. Determine characteristics

3.1 Scenario analysis

In order to understand on what scale the input parameters would affect the impact results, we conducted scenario analyses. The parameters manipulated for each scenario are listed below.

1. *Price ratio between primary product and waste/by-product*
The price ratio between primary product and waste/by-product was varied based on the historical price of the primary products for the economic allocation method. For example, based on historical high and low price for Spanish wine, the lower bound and higher bound for the wine price to grape-pomace price ratio were decided to be 0.22% and 2.02% (European Commission, 2020) (see Results 5.1 for more detail).

2. *Conversion ratio between waste/byproduct and substitution product*
Different conversion ratios are used based on the utility of interest. For example, when considering energy content, 1kg dry matter (DM) of grape pomace is equivalent to 1.136 kg DM of hay. However, when considering crude protein, 1kg DM of grape pomace is equivalent to 1.191 kg DM of hay (Gessner et al., 2015).

The conversion ratio between waste/by-product and substitution product was varied on a plus/minus 10% scale. Due to limited information on the utility of waste/byproduct, the accurate conversion ratio range cannot be determined. Hence, the 10% variation is a relatively arbitrary decision.

These two types of scenario analysis will be integrated into a flexible adjustment framework in the following section.

3. *Dehydration and transportation*

Dehydration and transportation are two common additional processes needed to transform the feedstocks before arriving at Apeel as functional feedstocks. Since the two processes differ significantly across the four feedstocks that we analyzed, they are not included in the baseline analyses.

For this analysis, we evaluated how the inclusion of an additional process (dehydration) would affect results for economic allocation and substitution methods. Since the water content of each feedstock was different this served as an interesting example of what can result from including additional processes. Appendix A elaborates on how the LCA framework would treat this additional process. In practice, the calculation is done in three steps:

1. Calculate how much water needs to be vaporized to get 1kg DM of the feedstock using its water content.
2. Calculate how much heat is needed to vaporize this water from room temperature using the specific heat of water.
3. Calculate the environmental impacts from the generation of this heat in the chemical industry and add the impacts to the baseline results. The actual heat consumption will be higher than the theoretical calculation results due to heat loss in the dehydration process, which is not accounted for in our analysis. Therefore, the results for dehydration can be thought of as lower bonds of the actual value.

The methodology could also be applied to transportation, which is essentially another additional process in the LCA. Instead of water content and heat consumption, we would evaluate the distance between the generation location of each feedstock and Apeel. Since there is no specific information regarding the waste generation location at this point, actual calculation for transportation is not included in this project.

3.2 Flexible adjustment framework

In actual applications, many analysis parameters would be highly dependent on specific scenarios. First, the prices of primary products and waste/by-products are subject to market conditions. This is especially true for waste/by-products. With limited information on waste/by-product markets, an opportunity cost approach was used in this project. However, it is possible that a mature market will be established for the waste/by-products in the future when more potential applications are discovered. In that case, the analysis would have a different price ratio. Similarly, the conversion ratio used in this project is based on the utility of interest as described in section 3.1, meaning that different conversion ratios will be needed for different scenarios.

In addition to these key parameters, an analyst may have additional information differentiating feedstock options. This additional information is situation specific but may include additional transformational processes (such as dehydration in the context of our case study).

In order to make the analysis in this project reproducible for future applications we created a flexible adjustment framework and tool informed by case study with Apeel. Essentially, this framework guides users through our analysis from the selection of feedstocks to the gathering of relevant information. The framework then directs users to our tool which enables uses to perform the same calculations used in our quantitative analysis.

Results

1. Feedstock profiles

Below we present the results of our initial supply chain research. We developed individual profiles for each feedstock and then generalized these findings into ways Apeel, or any organization, may use the information to assess a sourcing decision.

1.1 Olive Pomace

Olive pomace was initially classified as a by-product based on research compiled by Apeel. Within this classification it was grouped with cranberry pomace and tomato pomace based similar physical characteristics: all being pomaces. We decided to analyze olive pomace as there existed more life cycle assessment studies and literature on olive oil, olive waste and olive cultivation than the other options.

Description
Olives are traditionally grown in a Mediterranean climate, with the majority of the world's olive oil production centered in Europe; specifically, Spain, Italy and Greece (Vossen, 2013). Olive trees are biennial meaning they alternate between having highly productive years and years with low yields. During harvest, the trees are stripped of their olives which are promptly gathered and then processed into olive oil. The processing may occur on site or be transported to a separate facility.

Olive pomace refers to what remains of the initial olive after the oil is removed; it consists of a paste-like solid of the fruit and pit (Clodoveo et al., 2015). The pomace itself still contains small amounts of oil and other compounds that may be attractive to some firms (Clodoveo et al., 2015; Notarnicola et al., 2015).

Supply Chain

While olive oil can be created using various methods, these methods share similar processes. A condensed version of the supply chain is shown in Figure 5. In all cases, the first step in the supply chain is the cultivation of olive trees. This involves nurturing the tree by pruning as well as optional inputs like fertilizers and pesticides or herbicides. Once the trees are mature and bearing fruit, the olives are harvested and go through defoliation (the removal of leaves, twigs and other undesirable material) and washed. The main inputs to these two stages are water, and any energy that may be used to power machinery that may be used to facilitate these processes. There also may be energy inputs to power farm equipment.

The olives are then crushed into a paste-like consistency and go through a process known as malaxation. This process prepares the crushed olives to yield more oil, by mechanically facilitating the coalescence of oil droplets. The main input to this is energy.

This material is then centrifuged to separate the oil. Within the centrifugation step, there are two main systems: two-phase and three-phase. The difference between the two is that the three-phase system dilutes the paste with water, resulting with three outputs: oil, pomace, and "vegetation water." This technique has water and energy as main inputs. However, the two-phase system does not dilute the paste and results in only two outputs: pomace and oil. The pomace coming from the two-phase system is very moist, so much so that this pomace does not undergo further processing to become olive pomace oil (see "Common fate of waste" below) (Seçmeler & Galanakis, 2019). Therefore, our analysis focused on only three-phase systems. This technique also only has energy as a main input. With the pomace now separated, the oil goes on to be bottled.

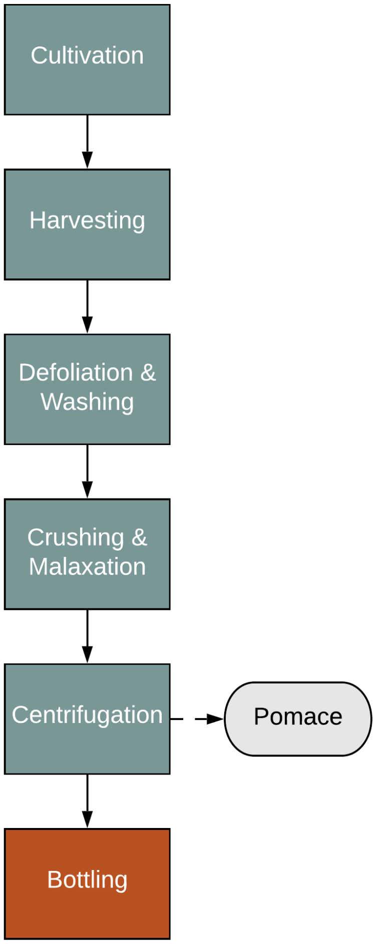

Figure 5. **Simplified olive oil supply chain.** Using the economic allocation methodology, the impacts from processes in blue are partially allocated to the waste product, pomace. The waste, olive pomace, is indicated in gray. The impacts from processes in orange are not allocated to the waste in either methodology as they occur downstream from the separation of the waste product.

End of life

If olive pomace is disposed of, it is usually landfilled or plowed directly back into fields. Olive pomace has high organic matter content, which requires treatment in order to be disposed of hygienically. Without treatment, it can cause environmental degradation to soil and surface waters of the areas it is disposed of (Azbar et al., 2004).

Other uses:

- Olive pomace still contains small amounts of oil and is often processed to extract the oil to make olive pomace oil, a secondary vegetable oil (Salomone & Ioppolo, 2012).
- Dried pomace (from either olive oil or olive pomace oil production) can be burned as a biofuel (Maragkaki, et al., 2015); Azbar et al., 2004).
- Olive pomace can be composted and applied back into fields (Salomone & Ioppolo, 2012; Arvanitoyannis & Kassaveti, 2007; Notarnicola et al., 2015; Altieri & Esposito, 2010; Cucci et al., 2013).
- Direct application to land as mulch (Notarnicola et al., 2015).
- Evaporation (natural through lagoons, or technological through vacuum or electrolysis) (Azbar et al., 2004; Notarnicola et al., 2015).
- Extraction of bioactive compounds (Clodoveo et al., 2015; Notarnicola et al., 2015).

1.2 Coffee Cherries

Coffee cherries were selected for analysis from a broader group that included citrus seeds and papaya seeds. These feedstocks were considered to have similar physical characteristics - all the waste represented seeds that had to be separated from the larger fruit. They also were all considered by-products by Apeel. They differ in location grown and main exporting countries; coffee and papaya are grown in tropical regions and are imported goods to the US, while citrus is grown in various locations around the U.S. Coffee cherries were selected in order to include a scenario where the original crop (coffee bush) was not grown in the U.S. Also, there existed more transparent data on alternate uses compared to papaya.

Description

Coffee berries are fruit harvested from coffee bushes. The coffee cherry refers specifically to the skin and flesh that surrounds the seed within the fruit. This seed, or bean, is the part that is commercially valuable - it is separated from the cherry, dried and then sold whole or ground. When separated from the cherry, the coffee seeds are often referred to as “green coffee beans”.

Coffee plants are native to the equatorial East African region, and are now grown in tropical climates across the globe. There are two main species of coffee grown for commercial use - *Coffea arabica* and *Coffea robusta*. Robusta coffee has a harsher flavor and is generally used for low grade coffee products, such as instant coffee. Arabica coffee tends to have a better taste and is therefore more popular with specialty roasters. Arabica accounts for over 70% of all coffee production (Chanakya & de Alwin, 2014).

Supply chain

The coffee supply chain is depicted Figure 6. There exist two main methods for processing coffee berries into green coffee beans - the wet and the dry method, both of which often occur on the farm where the berries are grown. The wet method uses large quantities of water: the coffee berries are squeezed between metal plates to separate the skin and pulp from the seed, and then streams of water are used to transport the skin and pulp into a receiving tank. From there, the pulp is separated out to form solid waste, with the remaining water creating a wastewater stream. Oftentimes these two streams are combined for disposal (Chanakya & de Alwin, 2014). The main inputs to this system are energy and water.

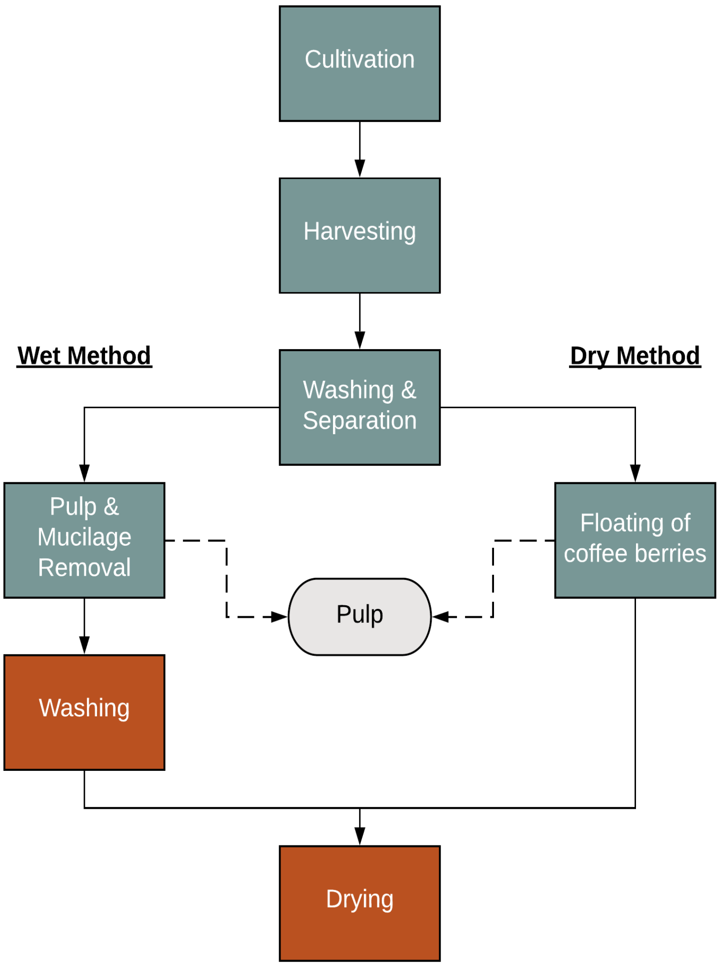

Figure 6. Simplified coffee supply chain. Using the economic allocation methodology, the impacts from the coffee production processes in blue are partially allocated to the waste product, pomace. The waste, a pulp consisting of coffee cherries and water, is indicated in gray. The impacts from processes in orange are not allocated to the waste in either methodology as they occur downstream from the separation of the waste product.

The dry method begins by laying whole coffee berries out to dry for 3-4 weeks after they are picked. They are then put into a hulling machine that separates the dry coffee cherry from the beans. This creates a single solid waste stream of the dried cherries. The main input to this system is energy to operate the hulling machines.

What method is used to process the berries depends on both the region where they are grown and the species of coffee. The wet method is more popular in regions with high precipitation and tends to produce higher quality coffee. It is also t more often used to process Arabica coffee. Beans processed using the dry method are subject to climatic conditions during the drying period, giving the processor less control over the outcome. For this reason, Robusta coffee destined for lower quality uses is more often processed using the dry method (Chanakya & de Alwin, 2004)

End of life

Waste resulting from the wet method of processing is either dumped or treated in anaerobic or aerobic. Assessments of farms in different geographic regions suggest that farmers often do not have the capital necessary to treat this waste (ASTRA, 2002). This effluent is highly acidic and has a large amount of suspended organic matter. Furthermore, if the coffee was treated with pesticides or herbicides, the wastewater may also have some level of toxicity (Chanakya & de Alwin, 2004). If dumped into waterways, the pollution can produce negative effects for nearby communities that rely on the water for domestic and agricultural use (Kassa & Workaheyu, 2015). However, treatment can also pose issues as leakage from these lagoons can contaminate groundwater (Chanakya & de Alwin, 2004).

Waste resulting from coffee berry processing may also be directly applied onto the farm as mulch without any treatment or further transformation, although the acidity and/or toxicity present can cause damage to the soil (Flysjo et al., 2006).

Other uses:

Despite many farmers choosing to dispose or treat coffee cherry waste streams, multiple alternate uses for this material have been identified. The most suitable use depends on the process used to separate the coffee cherry from the seed (wet or dry) due to the differences in the resulting material composition.

- Coffee cherries (both husks from dry processing and pulp from wet processing) can be composted successfully with either manure or plant material, forming a nutrient rich material for reapplication to soil (Kassa & Workaheyu, 2015).
- They can also be used as input to other industries. A study by Pedraza-Beltrán et al. (2012) tested coffee cherries as an additive to cattle feed, replacing maize, and found that both worked equally well to increase weight of individual cattle.
- Dry coffee cherries can also be burned as biofuel (Echeverria & Nuti, 2017; Chanakya & de Alwin, 2004).
- Other more fringe uses include creating a mulch or soil substrate that has been found to be particularly good for commercial mushroom cultivation. Specific compounds from coffee cherry waste can also be used as inputs for cosmetic products or nutritional supplements (Echeverria & Nuti, 2017).

1.3 Cocoa Husks

Cocoa husks were selected from a broader group that consisted of guava seeds and stone fruit pits. These parts were all considered to be wastes generated during the processing of fruits into other products. Cocoa husks were chosen to be analyzed as the corresponding primary product, chocolate, has a larger market - there is more cocoa grown for chocolate than there are guavas grown for an industrialized export market. Therefore, there existed better documentation of the supply chain and life cycle of this feedstock.

Description

Cocoa husk refers to the shell and kernel portions of a cocoa bean. The husk is separated from the desirable inner part of the bean, technically called the cotyledon but referred to as "nibs", during the chocolate manufacturing process (Okiyama, Navarro, & Rodrigues, 2017).

Cocoa beans are the seeds of the cocoa fruit, which grows on the cocoa tree. Due to the large global demand for cocoa-derived products, cocoa trees are often cultivated on plantations in the tropical regions of Africa, Asia, and the Americas (Recanati, Marveggio, & Dotelli, 2018).

Supply Chain
Cocoa can be harvested year-round, but there are typically two major harvest periods per year, six months apart. Once ripe, cacao pods are manually cut down from the trees and sorted based on pod quality. The cacao beans and pulp are scooped out quickly and laid out on mats or banana leaves or placed in a box with a lid. The beans are left to ferment for 5-7 days, then they're removed from the mats or boxes and dried in the sun for up to a week. In countries that lack pronounced dry climate periods, the beans may undergo an artificial drying process.

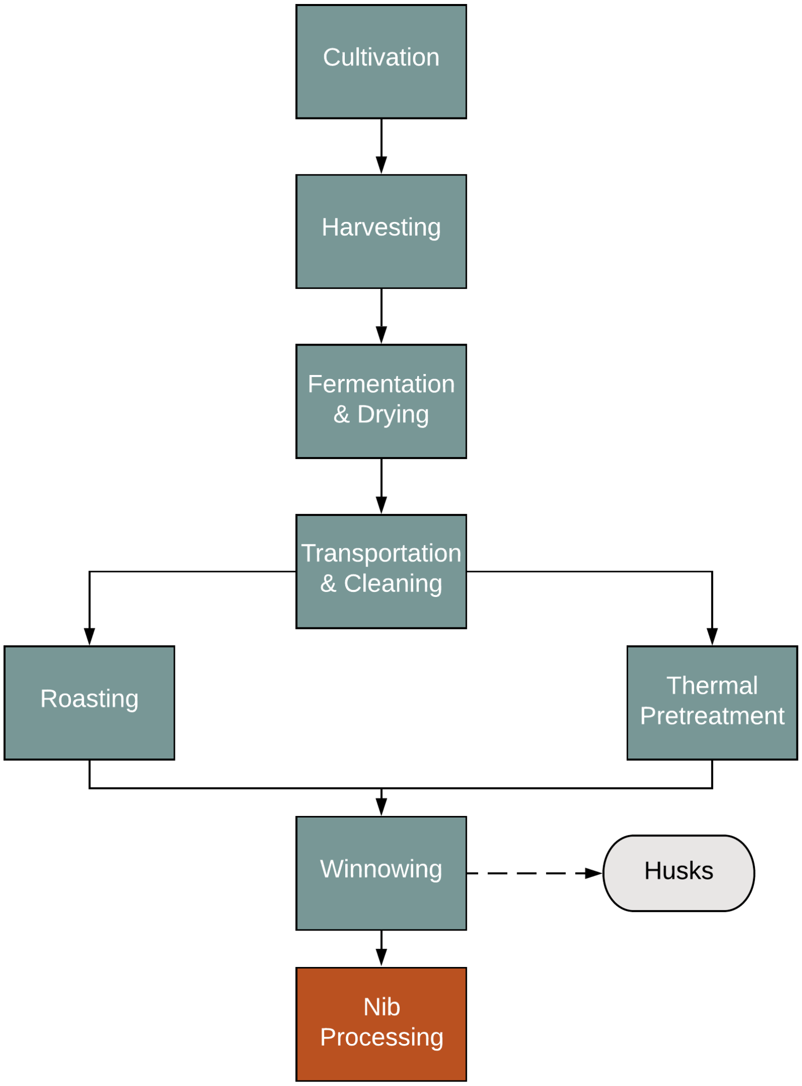

Figure 7. Simplified chocolate supply chain. Using the economic allocation methodology, the impacts from the chocolate production processes in blue are partially allocated to the waste product, pomace. The waste, cocoa husk, is indicated in gray. The impacts from process in orange are not allocated to the waste in either methodology as they occur downstream from the separation of the waste product.

Once dried, beans are stored or transported to a chocolate manufacturing plant. Here, the dry beans are cleaned to remove any debris, then they are roasted. After roasting, they are poured into a winnowing machine where the husks are separated from the nibs ("The Journey From Cacao Pod to Chocolate," n.d.). Another process that the beans may undergo is a thermal pretreatment, followed by breaking, shelling, and winnowing and then roasting. The husks are removed during the winnowing phase. After the nibs are isolated, they are processed into the desired cocoa derivatives (cocoa powder, cocoa butter, chocolate).

End of life
Cocoa husks are removed as part of the chocolate making processes, rather than on field. Therefore, the cocoa husks are usually combined with other wastes from the process and incinerated or landfilled (Recanati et al., 2018).

Other Uses:
If not sent to landfill or incinerated, the cocoa husks that accumulate from this process have the following alternative uses (Okiyama, Navarro, & Rodrigues, 2017; Green City Growers, n.d.):

- Burned as biofuel for the boilers in the chocolate factory.
- Used as animal feed
- Fertilizer preparation

1.4 Grape Pomace

Grape pomace was selected from a group including apple pomace, coffee grounds, and spent grains. Apeel had categorized this group as wastes. Grape pomace was selected in particular as it is primarily sourced from winemaking, and the viticulture industry is well documented in scientific literature.

Grapes destined for wine are cultivated in Mediterranean regions around the world. Roughly 7.5-7.9 million hectares of cropland are devoted to viticulture globally with Spain, France, Italy, and the United States occupying approximately 40% of the total land area used for viticulture (FAO, 2009). More than 60% of the wine produced worldwide comes from these four countries (Ferrara & De Feo, 2018).

Description

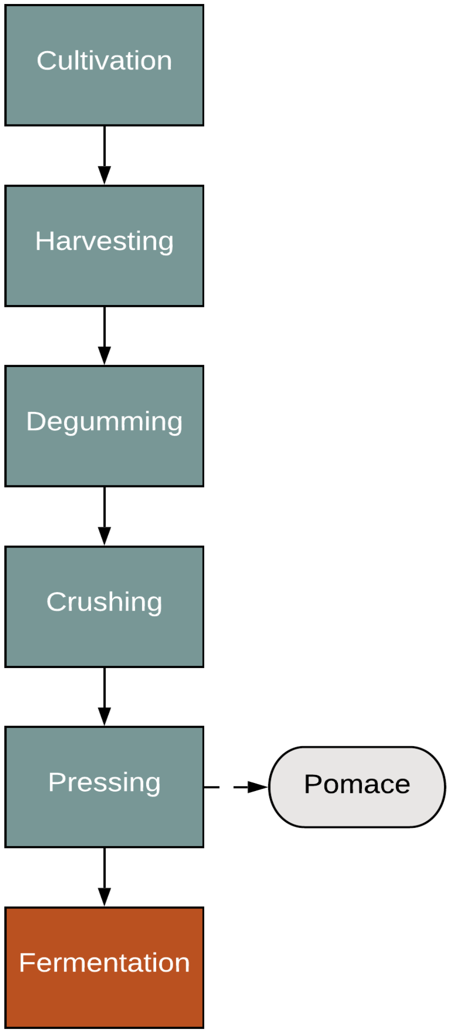

Figure 8. Simplified wine supply chain. Using the economic allocation methodology, the impacts from the winemaking processes in blue are partially allocated to the waste product, pomace. The waste, grape pomace, is indicated in gray. The impacts from processes in orange are not allocated to the waste in either methodology as they occur downstream from the separation of the waste product.

Grape pomace is a by-product of the winemaking process. It consists of substances leftover from the crushing process. This process releases fluid from the grapes, leaving behind skins, seeds and the flesh of the fruit.

Supply Chain
Figure 8 shows a simplified supply chain for the wine making process. After grapes are grown and harvested, they are crushed, de-stemmed, and pressed for their juices. The remaining solids (composed of the skins, seeds, and flesh of the grape) are referred to as grape pomace, also sometimes referred to as marc (Galanakis, 2017). This process is fairly universal in winemaking operations around the world. Red wine varietals are made by adding the additional step of fermenting the marc in the liquid for a period of time (Galanakis, 2017.).

The main inputs to the grape cultivation process are water and nutrient fertilizer. The harvesting, crushing, and pressing involve energy inputs (Poupart, 2017).

End of life
If disposed of, grape pomace is often landfilled (Galanankis, 2017). Due to its high organic matter, this can create harmful environmental impacts and therefore requires treatment in order to be disposed of hygienically.

Other uses:
Grape pomace contains valuable organic compounds found that can be synthesized into secondary products. These products include the following:

- Antioxidant extraction - high amounts of polyphenols, a natural compound found in plant material, make grape pomace a valuable source for antioxidants. This can be done through distillation (Rebecchi et al., 2013). These may be used as additives to other food products or cosmetic products (Dwyer et al., 2014).

- Animal feed – a study by Chedea et al. (2016) found that adding grape pomace to milk cow feed improved cow health and did not affect the quality of milk
- Compost - field experiments have shown that composted grape pomace works well as an additive to soil with low organic matter content (Bertran, Sort, Soliva & Trilllas, 2004).
- Biomethane production - grape pomace can be converted into biogas through anaerobic digestion (Rebecchi et al., 20130).

2. Key profile characteristics

From these detailed profiles, we extracted key characteristics that relate to the environmental impact of the feedstock (see Table 2 for summary). These characteristics can be thought of as the first considerations an organization should take when evaluating potential wastes as inputs. Although the scope of our project was not able to test how each of these characteristics might change the numeric results presented in the next section, we believe it is helpful in arriving at a decision for a company with a specific scenario or producer in mind. These are incorporated as the first steps in our decision framework and tool.

2.1 Geography

Knowing the geography of where the cultivation and/or processing happens can help companies start to think about both the estimated magnitude of the environmental impacts associated with the source as well as some of the related environmental and social issues that may be connected to a particular source. For example, feedstocks that are cultivated and/or produced in a country other than the U.S. will most likely have a larger impact due to the transportation needed to get the material to California-based Apeel. We did not include transportation explicitly in our calculations, as an analyst must know more details about the exact source to accurately assess the affect transportation may have. Rather, we consider it a scalar to the results, in that the total impact a sourcing option will have will increase as transportation distance increases.

Furthermore, the country from which a company is interested in sourcing may be an important consideration if the company values certain environmental impacts over another. For example, two of our supply chains under consideration, that of olive and grapes, are grown in Mediterranean climates that are frequently water stressed. If a company has incorporated protection of freshwater sources as one of their valued environmental outcomes, then it may be important to better understand how sourcing a feedstock from a supplier in the Mediterranean region may affect these issues, whether it be positive or negative.

The country of origin may also determine which groups of people carry the burden of environmental impacts associated with industrial food waste. For example, coffee is mainly cultivated in developing countries that usually do not have strong environmental institutions or regulations governing the agricultural sector. In this case, the negative environmental effects associated with either disposal of the waste feedstock or any other change to the supply chain falls mainly on the farmers and other members of rural communities. In comparison, a country with stronger regulations may have standards to handle large scale waste so that there are fewer environmental impacts that are also less likely to affect already disadvantaged populations.

2.2 Common Fate

Building on the idea that some populations may feel the impacts of industrial agricultural waste more than others, it is useful for companies to understand if the waste is actually disposed of and what the resulting negative impacts might be. If the waste is disposed of in a majority of cases, like that of coffee cherries, then that feedstock may be a better candidate for analysis than one that has many existing alternative uses (in essence, one that is rarely a true waste). This may also depend on what specific producers a company decides to source from.

2.3 Supply chain

Obtaining an understanding of the primary product supply chain that generates the waste feedstock in question can also help companies gauge what processes might be important when assessing the magnitude of the environmental impact. For example, if the feedstock is separated from the primary product early in the supply chain, then there are overall fewer processes needed to create the product. These processes are important to consider if the analyst uses the allocation methodology to quantify the environmental impacts. Furthermore, the extent to which the processes are mechanized and consolidated may be an important consideration - a product that is produced through highly industrialized processes may incur more environmental impacts or could also have lesser impacts if this creates high efficiency. The extent mechanized/industrialized may also help companies consider social issues as this may affect what groups benefit from a change in the fate of the waste generated.

This categorization is displayed in the table below for our case study feedstocks, from Apeel's decision making perspective:

Table 2. Key feedstock characteristics. A summary categorizing each feedstock in our case study based on geography, supply chain and common fate. This demonstrates an example of how analysts can begin differentiating options based on specific goals or priorities an organization may have.

Characteristic		**Olive**	**Coffee**	**Grape**	**Cocoa**
Geography	Cultivation	Domestic / Foreign	Foreign	Domestic / Foreign	Foreign
	Processing	Domestic / Foreign	foreign	Domestic / Foreign	Domestic

	Social	European countries, strong environmental regulations	Developing countries with weaker regulations, high poverty rates	North American and European, stronger regulation	Developing countries with weak regulations, high poverty rates
	Environment	Water stressed climates	High biodiversity, carbon sinks	Water stressed climate	High biodiversity, carbon sinks
Supply Chain	Point of separation	Mid separation	Early separation, small scale	Mid separation, medium scale mechanized	Late separation
	Extent Mechanized	Medium to large scale, mechanized	Less mechanized	Mechanized	Highly mechanized, industrial
Common Fate		Landfill	Landfill, Direct disposal to soil or water	Landfill	Biofuel

3. Scenarios for analysis

Based on the profiles of the four feedstocks selected, we developed scenarios to analyze our next objective: quantifying potential impacts using two different LCA methodologies. The primary product specifies which supply chain was considered with the allocation methodology, while the potential use refers to the alternative product considered in the substitution analysis. The scenarios were built based on what we found to be the most likely alternative use for the waste feedstock, and what data was most available. Because all four feedstocks can be composted into an organic fertilizer, we chose to conduct the substitution analysis with fertilizer as a possible fate for all four. We also conducted the analysis with another possible use for the feedstock that may differ across each feedstock. Animal feed is used for both coffee and grape pomace as this option has the most adequate data for both feedstocks (Table 3).

Table 3. Summary of sourcing scenarios selected for analysis. Each feedstock was analyzed under several possible scenarios. Under the substitution method, an alternate use specific to the individual feedstock was analyzed along with a shared alternate use, fertilizer. For economic allocation, each feedstock was analyzed as a by-product of its most common primary product.

	Olive	Grape	Coffee	Cocoa
Substitution	Secondary Oil & Fertilizer	Animal Feed & Fertilizer	Animal Feed & Fertilizer	Biofuel & Fertilizer
Economic Allocation	From Olive Oil	From Wine	From Coffee	From Chocolate

4. Baseline Results

Environmental impacts were calculated for all four impact categories using two methods: economic allocation and substitution with an alternative use, plus with fertilizer. For these results, the absolute values of the impacts are less relevant than the comparison between the different options.

The following figures compare these results side by side for each of the impact categories. Based on these results, we determined the feedstock with the lowest impact in each impact category and within one methodology. These are summarized in Table 4.

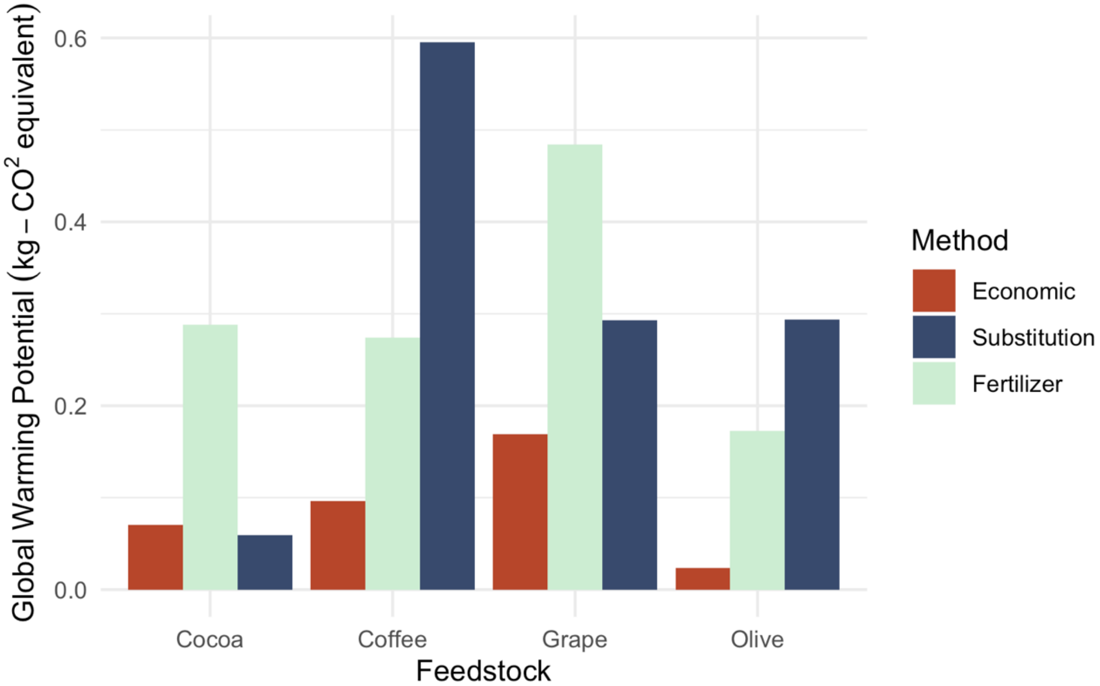

Figure 9. Baseline results for global warming potential. The colors refer to which method was used to calculate the result, with red as economic allocation, green as substitution using differing alternative uses, and blue as substitution using fertilizer. Higher bars depict a larger impact.

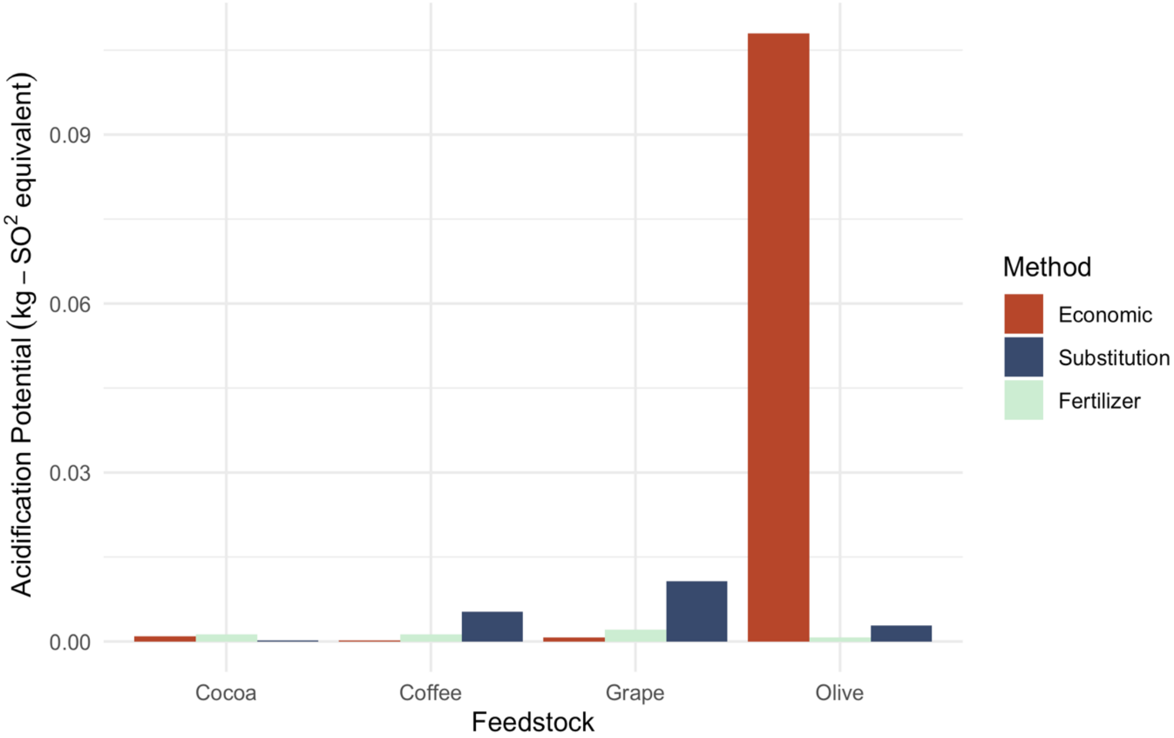

Figure 10. Baseline results for acidification potential. The colors refer to which method was used to calculate the result, with red as economic allocation, green as substitution using differing alternative uses, and blue as substitution using fertilizer. Higher bars depict a larger impact

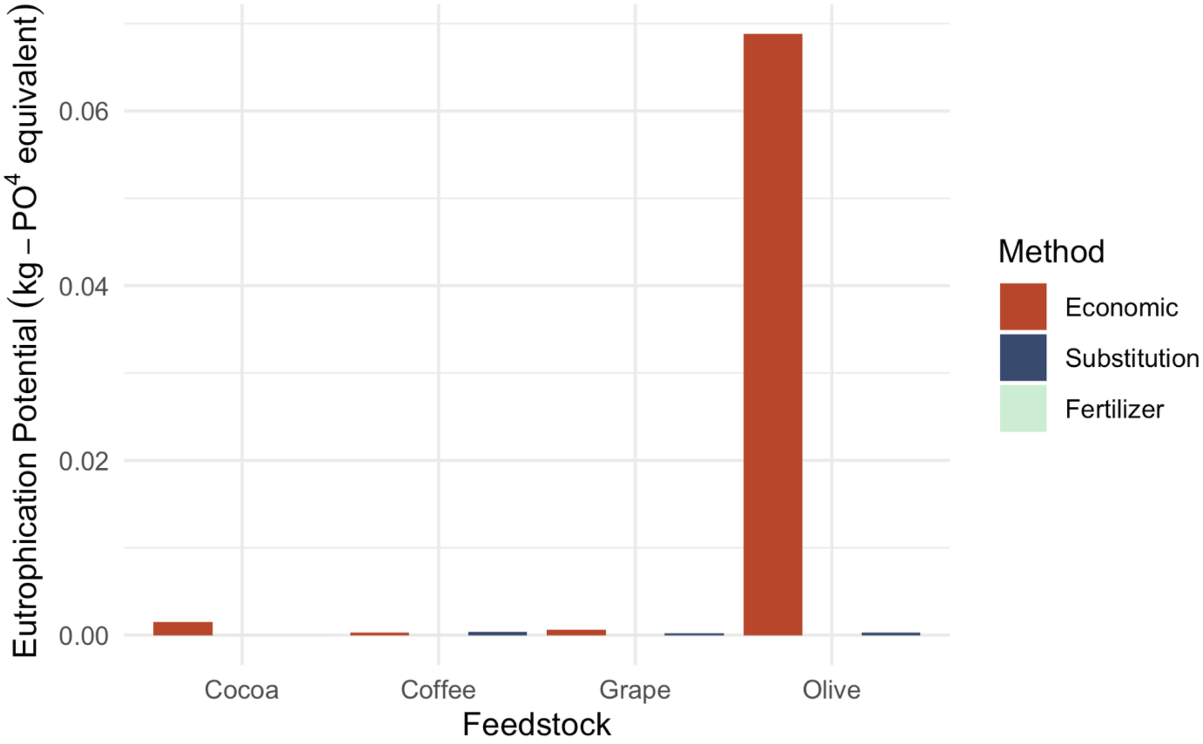

Figure 11. Baseline results for eutrophication potential. The colors refer to which method was used to calculate the result, with red as economic allocation, green as substitution using differing alternative uses, and blue as substitution using fertilizer. Higher bars depict a larger impact.

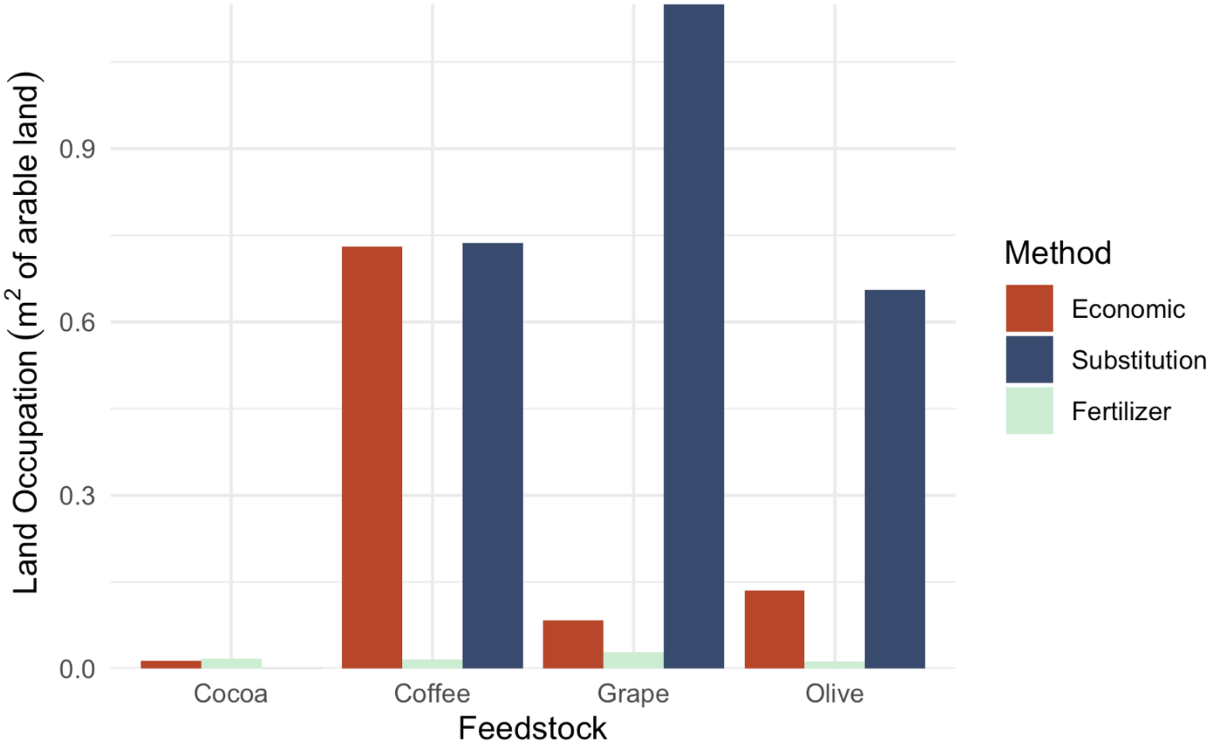

Figure 12. Baseline results for land use. The colors refer to which method was used to calculate the result, with red as economic allocation, green as substitution using differing alternative uses, and blue as substitution using fertilizer. Higher bars depict a larger impact.

Table 4. Summary of which feedstock had the lowest impacts in each impact category and for both methods used. Cocoa husks for biofuel were always the least impactful choice when using the substitution method, while for the economic method the least impactful feedstock was contingent on the impact category.

Impact Category	Substitution	Economic
Acidification potential	Cocoa husks for biofuel	Coffee cherries
Eutrophication potential	Cocoa husks for biofuel	Coffee cherries
Global warming potential	Cocoa husks for biofuel	Olive pomace
Land occupation	Cocoa husks for biofuel	Cocoa husks

As described above, three out of the four feedstocks had the lowest results in at least one impact category. Additionally, within an impact category the feedstock with the lowest impact differs depending on methodology, with the exception of land occupation.

The following figures show a direct comparison of the two methods. Each figure pertains to one impact category with the impacts calculated by economic allocation plotted on the x-axis and the impacts calculated by substitution on the y-axis. Additionally, a line has been added to each graph that plots the points where the impacts of the two methods (economic allocation and substitution) are equal. This creates quadrants on the figure that signal "optimal" or "poor" choices. Feedstocks that are in the lower left corner have low impacts as calculated by each method and are therefore more optimal, whereas feedstocks in the upper right have high impacts from each method and are therefore poor choices.

Within global warming potential, three of the four feedstocks have higher impacts when using the substitution method. This also highlights that when using economic allocation, olive pomace would have the lowest impact, whereas cocoa husks have the lowest when the substitution method was used.

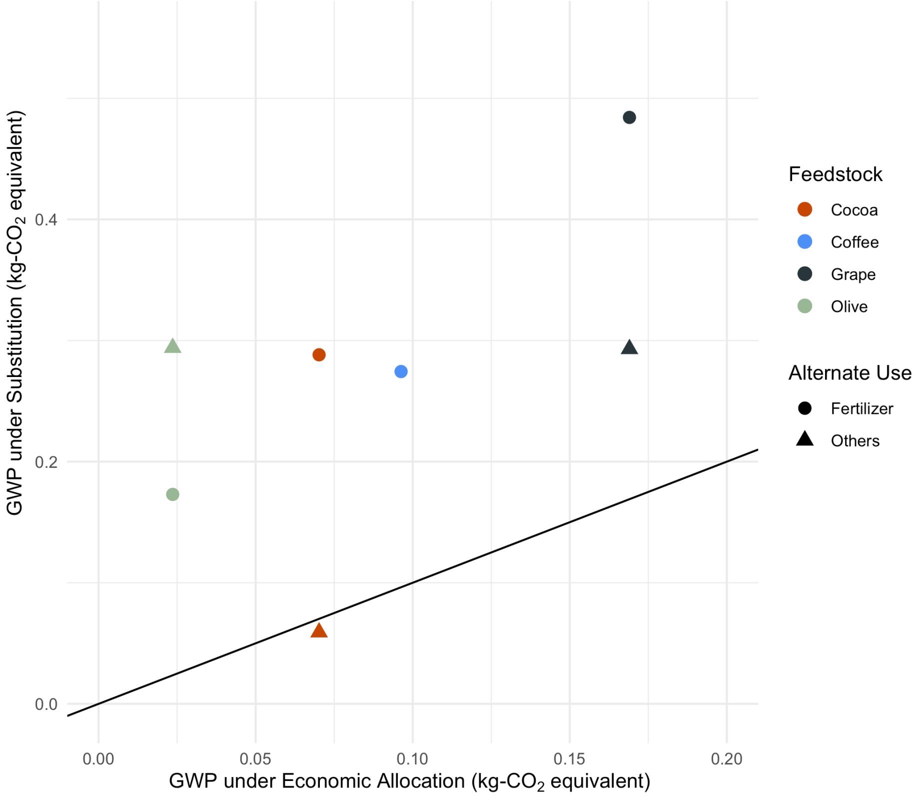

Figure 13. Economic allocation compared to substitution for Global Warming Potential. Baseline results for each tested scenario are plotted according to their impacts as calculated by economic allocation (along the x-axis) and by substitution (along the y-axis). Shapes are used to distinguish between the alternative uses of the feedstock, with the circles representing the case of fertilizer and triangles to show the other alternative uses. Colors are used to distinguish between feedstocks, with red representing cocoa, light blue coffee, dark blue grape and green olive. The black line is a 1-to-1line marking points at which economic allocation and substitution are equal to one another.

For eutrophication potential, coffee cherries had the lowest impacts by economic allocation while cocoa husk for biofuel had the lowest impacts by substitution. Olive pomace stands out as a feedstock that has a fairly large impact under both methods, particularly economic allocation. Acidification potential showed a similar trend as eutrophication, but with all the feedstocks other than olive and cocoa for biofuel showing larger impacts when using the economic allocation method (Figures 14 & 15).

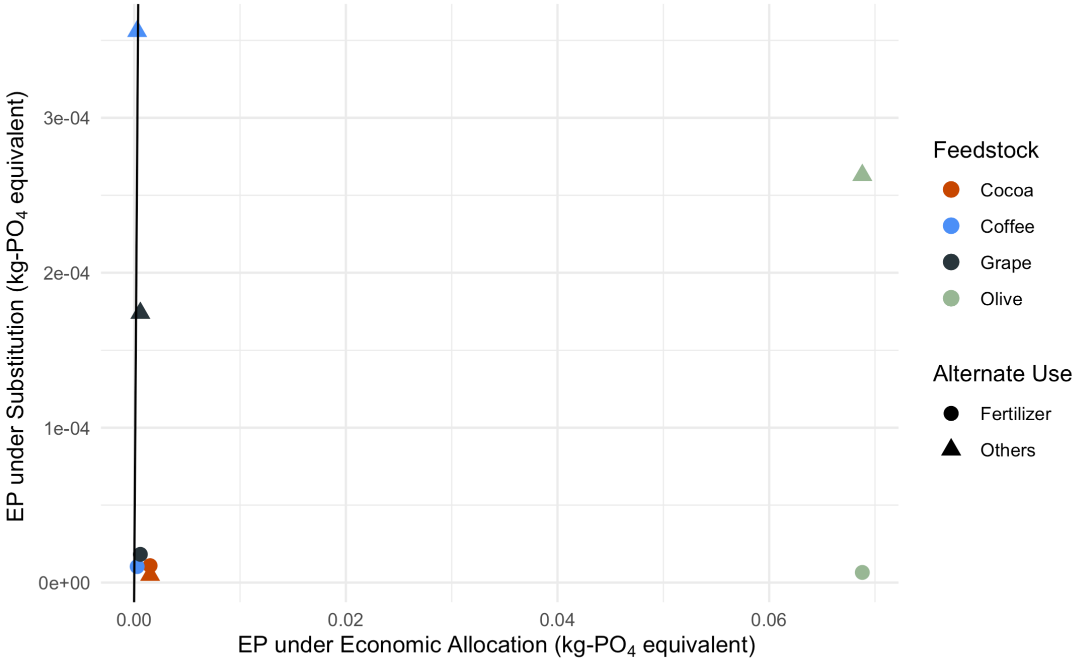

Figure 14. Economic allocation compared to substitution for Eutrophication Potential. Baseline results for each tested scenario are plotted according to their impacts as calculated by economic allocation (along the x-axis) and by substitution (along the y- axis). Shapes are used to distinguish between the alternative uses of the feedstock, with circles representing the case of fertilizer and triangles to show the other alternative uses. Colors are used to distinguish between feedstocks, with red representing cocoa, light blue coffee, dark blue grape and green olive. The black line is a 1-to-1 line marking the points at which economic allocation and substitution are equal to one another.

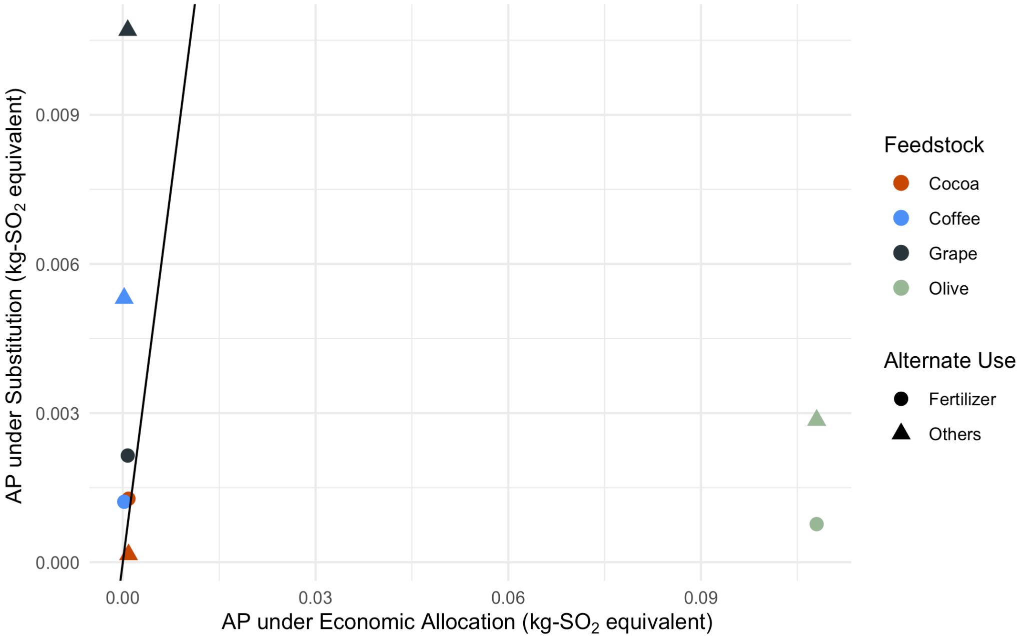

Figure 15. Economic allocation compared to substitution for Acidification Potential. Baseline results for each tested scenario are plotted according to their impacts as calculated by economic allocation (along the x-axis) and by substitution (along the y-axis). Shapes are used to distinguish between the alternative uses of the feedstock,

with circles representing the case of fertilizer and triangles to show the other alternative uses. Colors are used to distinguish between feedstocks, with red representing cocoa, light blue coffee, dark blue grape and green olive. The black line is a 1-to-1 line marking the points at which economic allocation and substitution are equal to one another.

For land occupation two of four feedstocks had a higher impact as calculated by the substitution method. This also shows that under both economic allocation and substitution, the feedstock with the lowest impact was cocoa husks. This was the only impact category in which a single feedstock had the lowest impact with both methodologies.

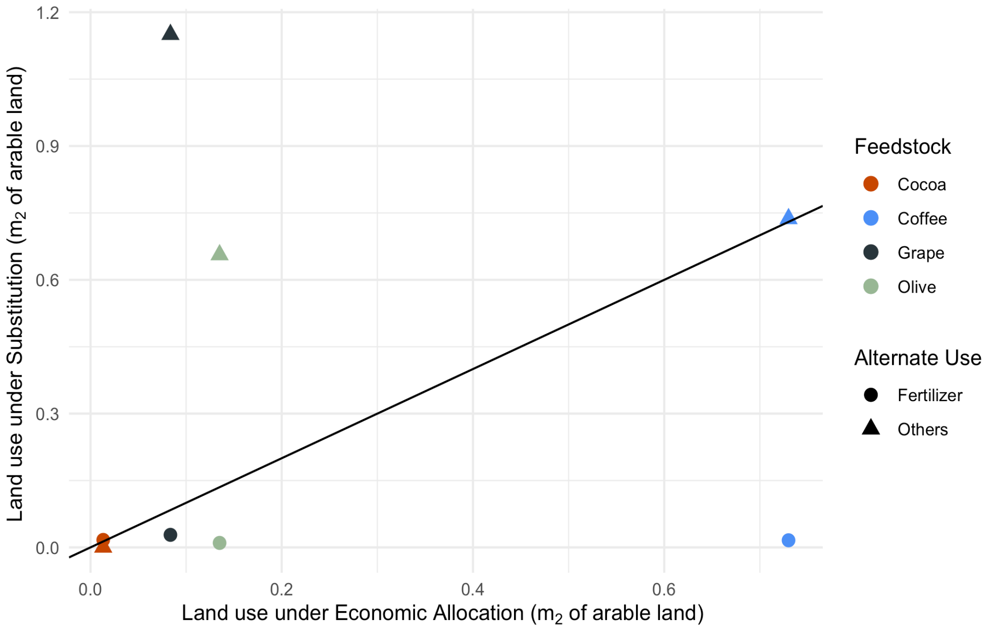

Figure 16. Economic allocation compared to substitution for Land Occupation. Baseline results for each tested scenario are plotted according to their impacts as calculated by economic allocation (along the x-axis) and by substitution (along the y-axis). Shapes are used to distinguish between the alternative uses of the feedstock, with circles representing the case of fertilizer and triangles to show the other alternative uses. Colors are used to distinguish between feedstocks, with red representing cocoa, light blue coffee, dark blue grape and green olive. The black line is a 1-to-1 line marking the points at which allocation and substitution are equal to one another.

5. Scenario analysis

5.1 Primary product price

Based on the historical prices of the primary products, we generated high and low-price scenarios for each feedstock (Table 5). The objective was to determine if there was a feedstock that, regardless of price scenario, still had lower impacts relative to the other feedstocks for each impact category. This would signal that a particular feedstock might be a better overall choice for Apeel regardless of market dynamics.

Table 5. Summary of the range of prices used for the economic scenario analysis and the resulting range in price ratio. Price ranges and the resulting percentage of allocated impact are reported for each feedstock. Despite differing currency units resulting from different data sources, we calculated a primary product to waste price ratio which is unitless. This ratio is what was used to allocate the impacts.

Feedstock	Price Range	Allocated Impact
Cocoa	0.89 - 3.13 USD/kg	2.49% - 8.3%
Coffee	1.13 - 2.85 USD/lb	5.52% - 18.07%
Grape	2.55 - 24.33 euros/kg	0.22% - 2.02%
Olive	1.61 - 4.03 euros/kg	5.07% - 11.82%

Overall, the economic scenario analysis did not reveal any obvious choices across all impact categories or within impact categories. For global warming potential, olive was somewhat differentiated from the rest as its highest price scenario still resulted in lower GWP (0.047 kg of CO_2e per kg of waste) than the lowest scenario for coffee cherries (0.051kg of CO_2e per kg of waste) and cocoa husks (kg of CO_2e per kg of waste) (Figure 17). However, the low scenario for grape pomace was still lower than the highest scenario for olive.

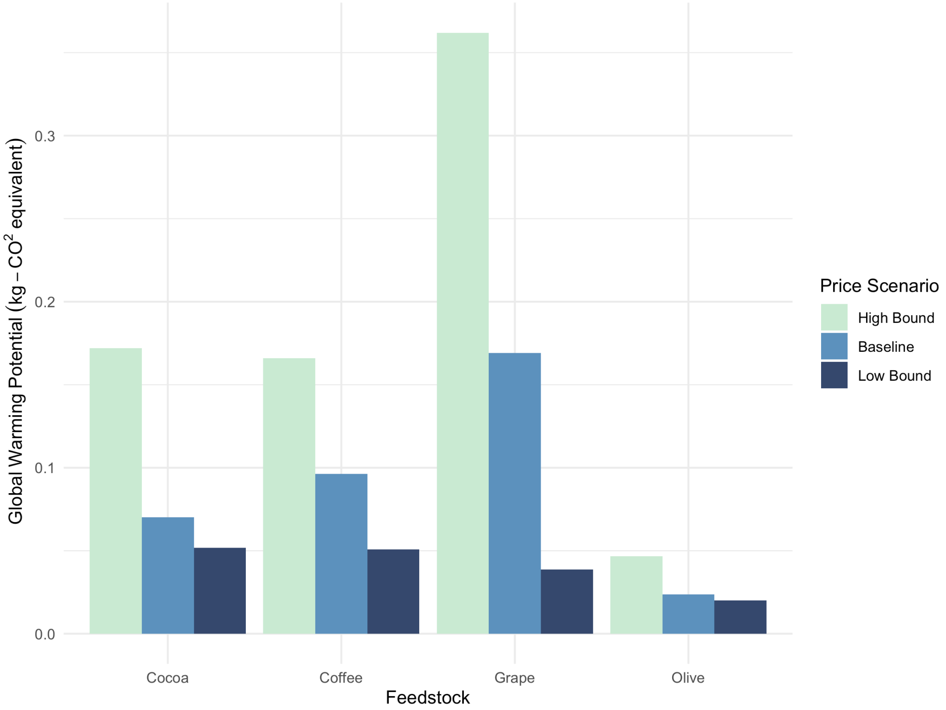

Figure 17. Price scenario analysis for Global Warming Potential. Green bars represent a scenario with high priced primary products, the light blue bars represent baseline results, and dark blue represents the low-priced primary product scenario. A scenario with a high-priced wine product stands out with the highest impacts, with the baseline and low-priced olive oil scenarios having the lowest.

Opposite the results for global warming potential, the results for both acidification potential and eutrophication potential show that olive pomace has the highest environmental impacts regardless of scenario, signaling that it actually may be a poor choice if these impact categories were prioritized (Figure 18 A & B).

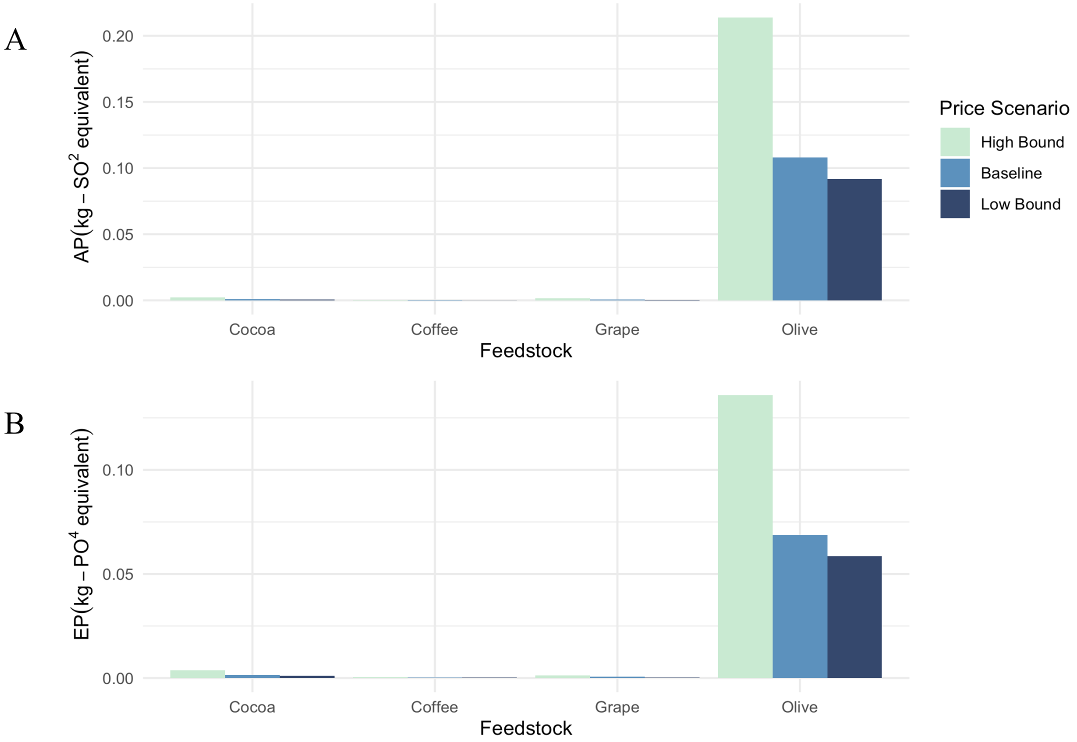

Figure 18. Price scenario analysis for Acidification Potential (AP) and Eutrophication Potential (EP). Green bars represent a scenario with high priced primary products, the light blue bars represent baseline results, and dark blue represents the low-priced primary product scenario. All three olive oil price scenarios have substantially higher impacts than the rest of the feedstock price scenarios.

If we isolate results for coffee and cocoa, coffee cherries show lower acidification potential and eutrophication potential than cocoa in all three scenarios. Therefore, while the full results make it difficult to isolate one choice out of the four that may be best, if a company had already narrowed the pool down to coffee and cocoa (perhaps reflecting an interest in sourcing from tropical geographies), this differentiation may be useful.

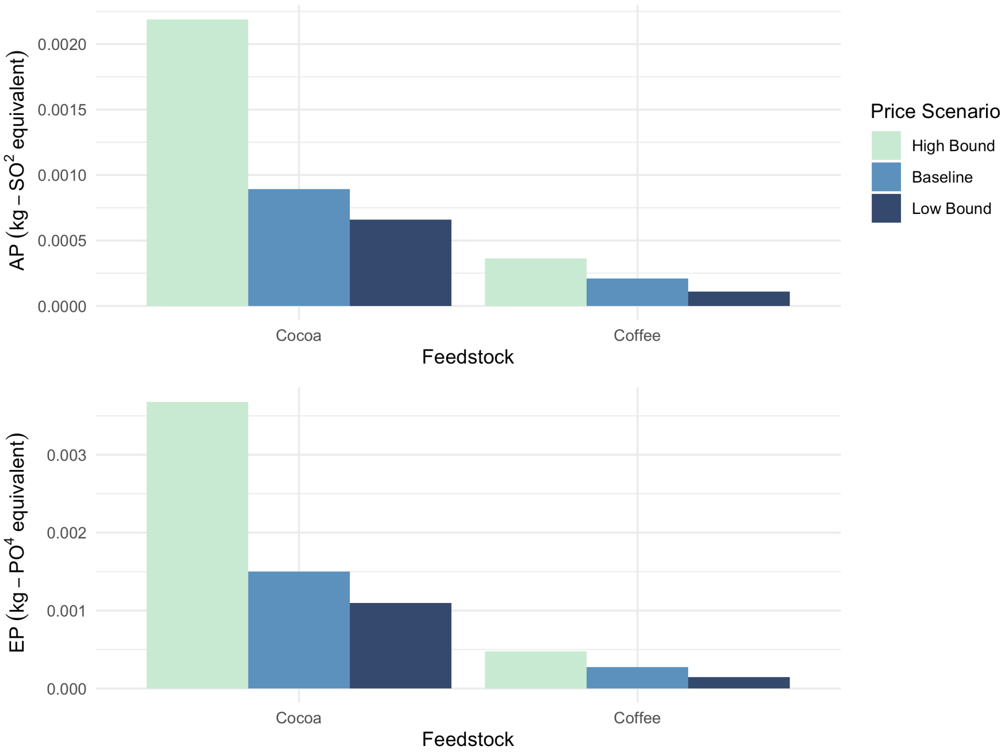

Figure 19. Price scenario analysis for Acidification Potential (AP) and Eutrophication Potential (EP) for coffee cherries and cocoa husks only. Green bars represent a scenario with high priced primary products, the light blue bars represent baseline results, and dark blue represents the low-priced primary product scenario. For these two feedstocks, all three coffee price scenarios have lower impacts than any of the chocolate price scenarios.

The results for land occupation show more differentiation between feedstocks. Figure 20 shows that all of the coffee cherry scenarios have impacts that are greater than the rest of the feedstocks. Furthermore, cocoa husks are differentiated from olive pomace as it's high scenario (3.25 x 10^{-2} kg m^2 arable land per kg of waste) is less than the low scenario of olive pomace (1.15 x 10^{-1} kg m^2 arable land per kg of waste).

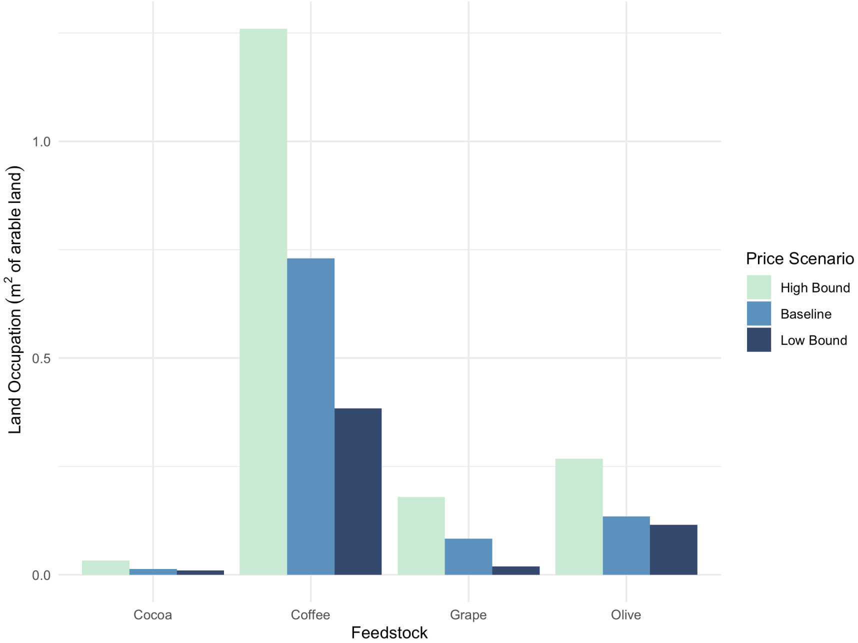

Figure 20. Price scenario analysis for Land Occupation. Green bars represent a scenario with high priced primary products, the light blue bars represent baseline results, and dark blue represents the low-priced primary product scenario. All three coffee price scenarios have the highest impacts.

Within economic allocation, three of the four impact categories had a clear most impactful feedstock (i.e. the feedstock with the highest impacts was differentiated from all other feedstocks. However, none of the impact categories had a clear feedstock with the lowest impact.

5.2 Substitution Ratio

The scenario analysis within the substitution method was performed by changing the substitution ratio by +/- 10% relative to the baseline. The results were calculated for each of the four impact categories for all alternative uses; the one exception being fertilizer from olive pomace. This was the one scenario with enough data on the nutrient content of olive pomace to form a more targeted range for the scenario analysis. As such, this scenario analysis was based on the range in nitrogen content of olive pomace. This resulted in a high scenario that was +33% of the baseline and a low scenario that was -30% of the baseline.

The results for global warming potential clearly show both a feedstock with the highest impact (coffee cherries for animal feed) and with the lowest impact (cocoa husk for biofuel) (Figure 21). The impacts for cocoa husks for biofuel range from 0.0532-0.0650 kg of CO_2e per kg of waste, the smallest range amongst the feedstocks within global warming potential. Olive pomace as fertilizer was isolated as the second least impactful, however its impacts are over twice that of cocoa husks for biofuel. The non-fertilizer alternative uses for grape and olive pomace (animal feed and secondary oil respectively) had almost identical results for every scenario, but these results fell within the range of other tested scenarios.

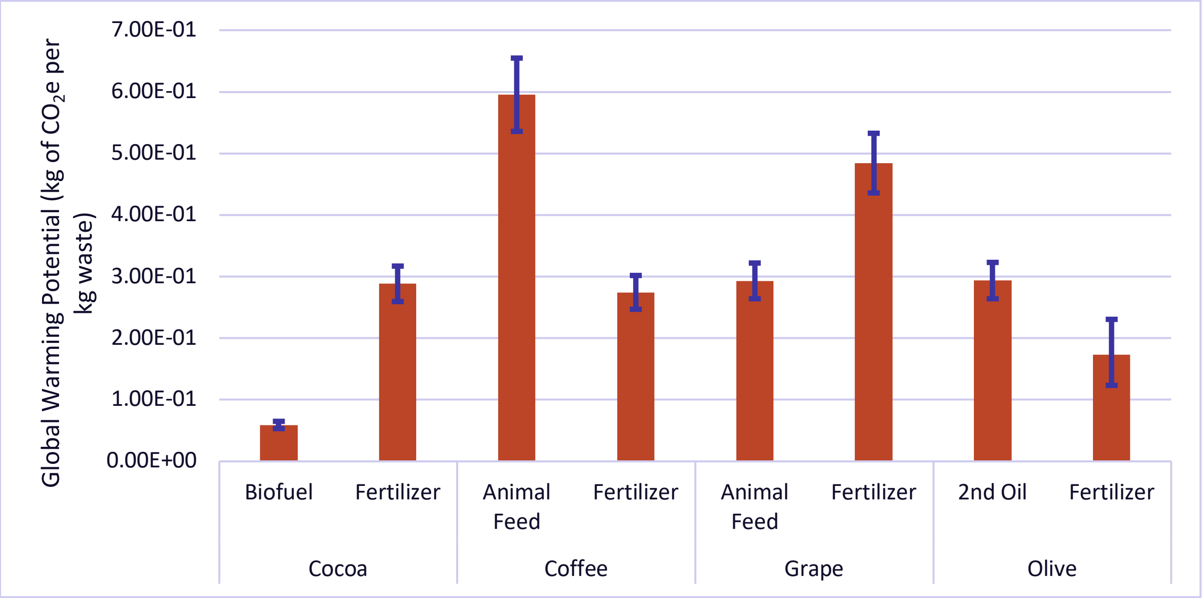

Figure 21. Global Warming Potential results for the substitution scenario analysis. Baseline results for Global Warming Potential are displayed by the blue bars for each alternative use. The error bars represent the impacts of different scenarios tested for each alternative use. The upper error bar uses a substitution ratio that is 10% greater than the baseline. The lower error bar uses a substitution ratio that is 10% less than the baseline.

Similar to the results using economic allocation, the results for acidification potential and eutrophication potential using substitution are somewhat parallel. The difference being that varying the substitution ratio results in clear “best” and “worst” choices within each impact category. These two categories had the most differentiation. Eutrophication potential shows cocoa for biofuel and olive for fertilizer again being the two best choices, however they are not differentiated from one another (Figure 22).

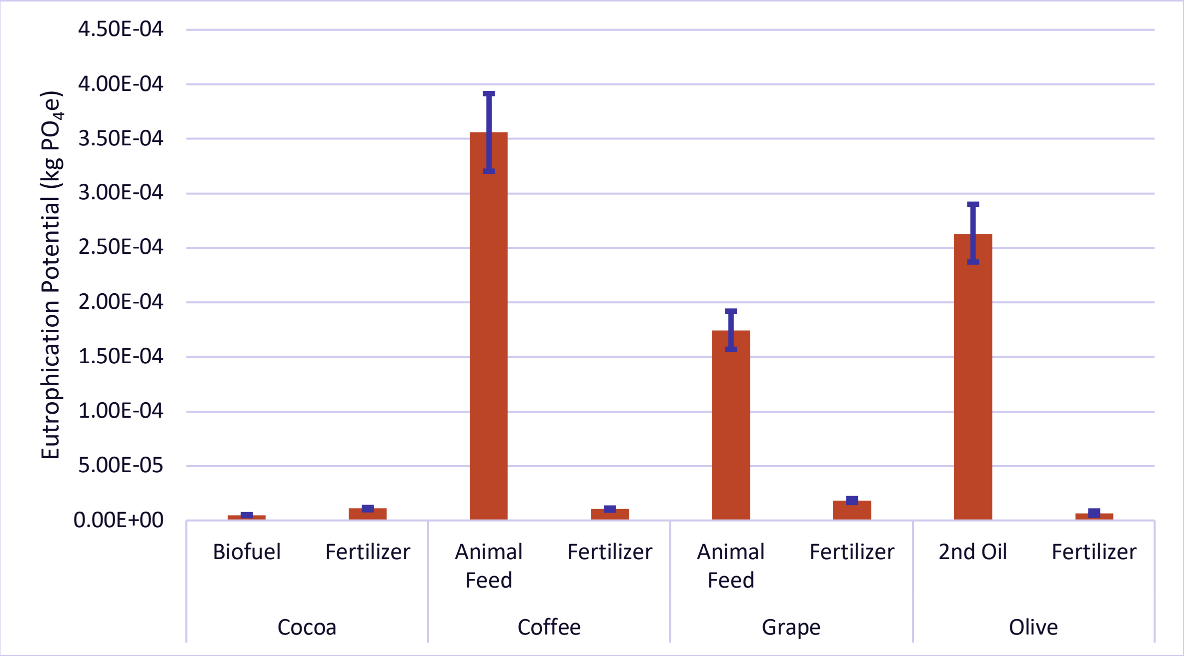

Figure 22. Eutrophication Potential results for the substitution scenario analysis. Baseline results for Eutrophication Potential are displayed by the blue bars for each alternative use. The error bars represent the impacts of different scenarios tested for each alternative use. The upper error bar uses a substitution ratio that is 10% greater than the baseline. The lower error bar uses a substitution ratio that is 10% less than the baseline.

Lastly, land occupation had the fewest differentiated scenarios using the substitution method. Cocoa for biofuel was the least impactful, followed by olive for fertilizer. The only other differentiated scenario was grape pomace for animal feed, which had the most impact.

The scenario analysis for the substitution method revealed more cases in which scenarios are differentiated from one another. First, cocoa for biofuel was always the least impactful and olive for fertilizer was always second (except in eutrophication potential in which the two were undifferentiated from each other). Second, for all impact categories, either coffee cherries for animal feed or grape pomace for animal feed was the most impactful scenario.

5.3 Dehydration

The effects of including dehydration as an additional process are analyzed for all four feedstocks under economic allocation and substitution for nitrogen fertilizer.

Figure 20 shows the global warming potential with the dehydration process under economic allocation. Although "wetter" feedstocks such as grape pomace, olive pomace, and coffee cherries show higher impact from the dehydration process, the order of GWP impact for the feedstocks is still the same as the baseline scenario.

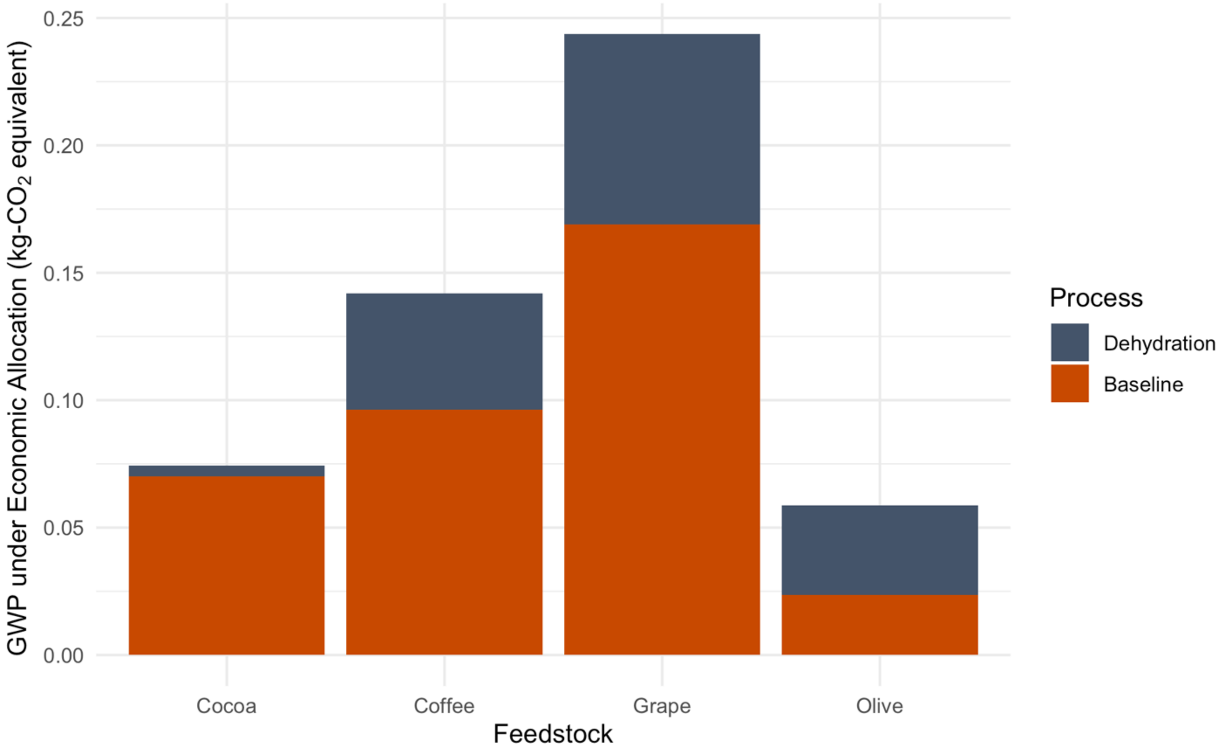

Figure 23. Global Warming Potential with dehydration process (Economic). Red bars indicate the baseline results with blue indicating the additional impacts incurred when adding dehydration to the process. The inclusion of dehydration does not change the ranking of feedstocks in terms of GWP impact for economic allocation.

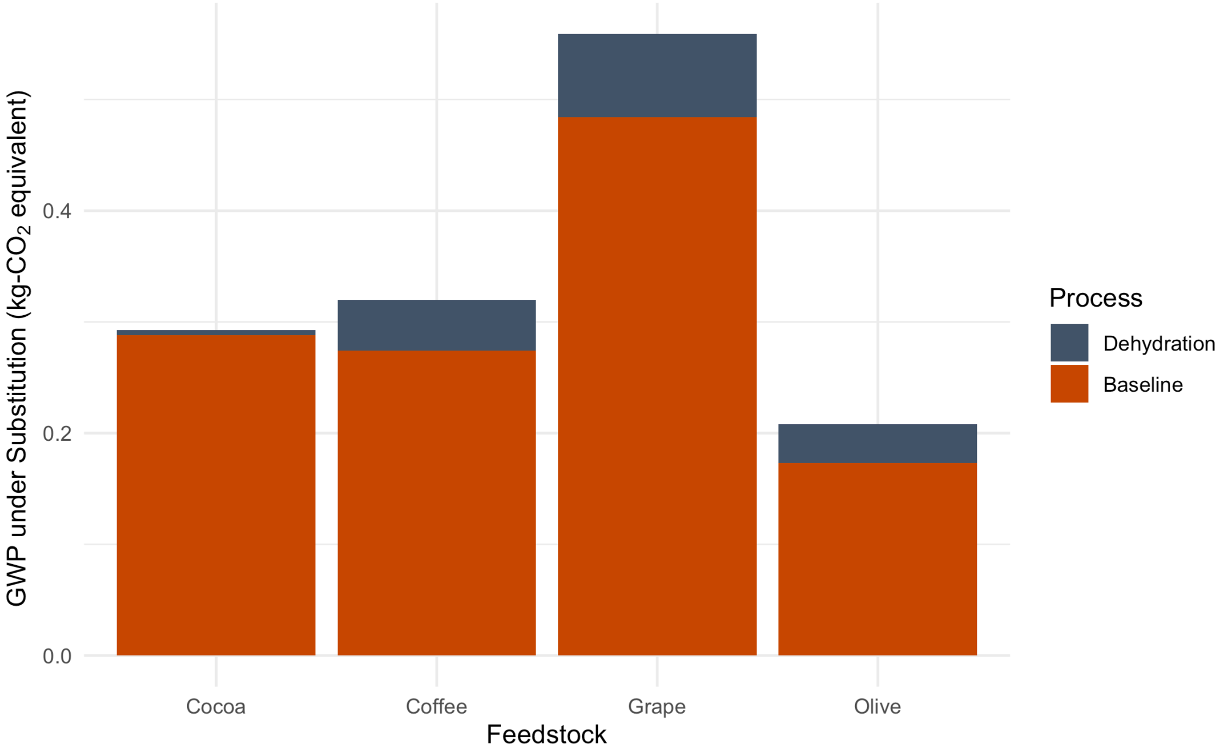

Figure 24. Global Warming Potential with dehydration process (Substitution for N Fertilizer). Red bars indicate the baseline results with blue indicating the additional impacts incurred when adding dehydration to the process. The inclusion of dehydration does change the ranking of feedstocks in terms of GWP impact for the substitution method.

On the other hand, Figure 24 shows the global warming potential with the dehydration process under substitution for N fertilizer. Higher GWP impact from the dehydration of the coffee cherries make it less preferable than cocoa husks, while in the baseline scenario coffee cherries was the more preferable option.

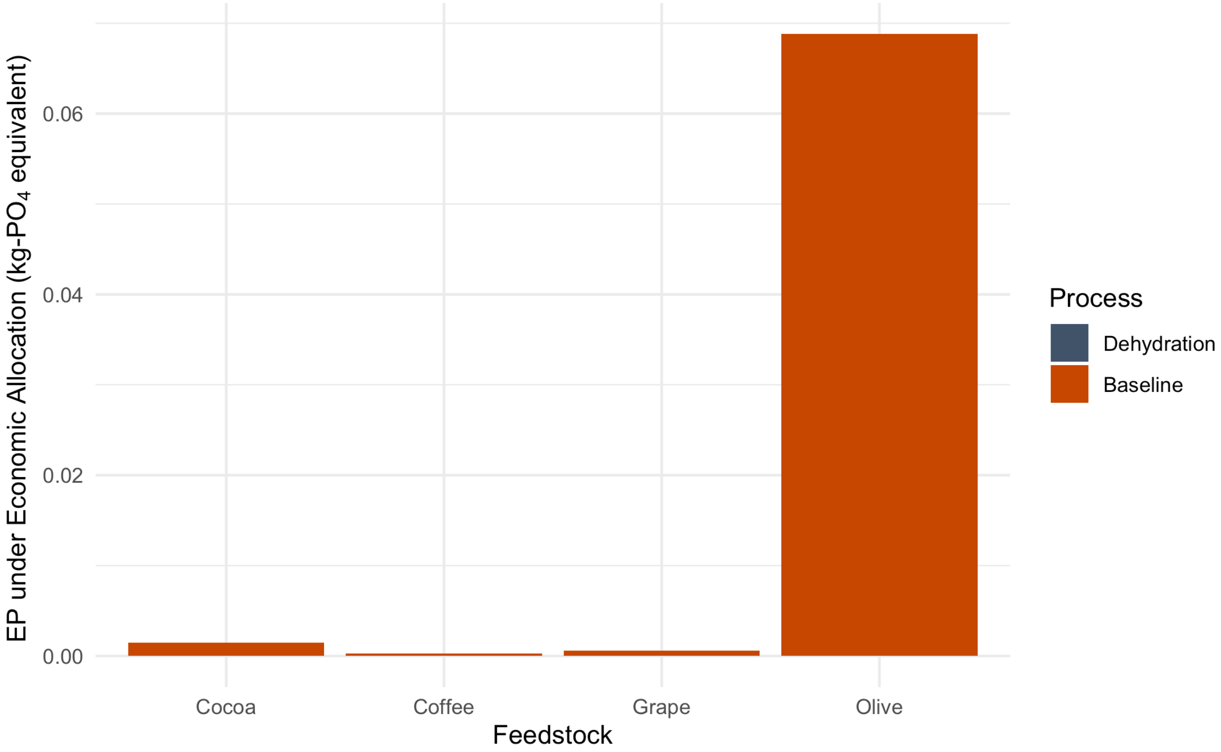

Figure 25. Eutrophication Potential with Dehydration Process (Economic). Red bars indicate the baseline results with blue indicating the additional impacts incurred when adding dehydration to the process. The inclusion of dehydration does not change the order of EP impact for economic allocation.

Figure 25 shows the eutrophication potential with the dehydration process under economic allocation. Due to the high EP impact from olive production and the low EP impact from dehydration, the result is almost identical to the baseline scenario.

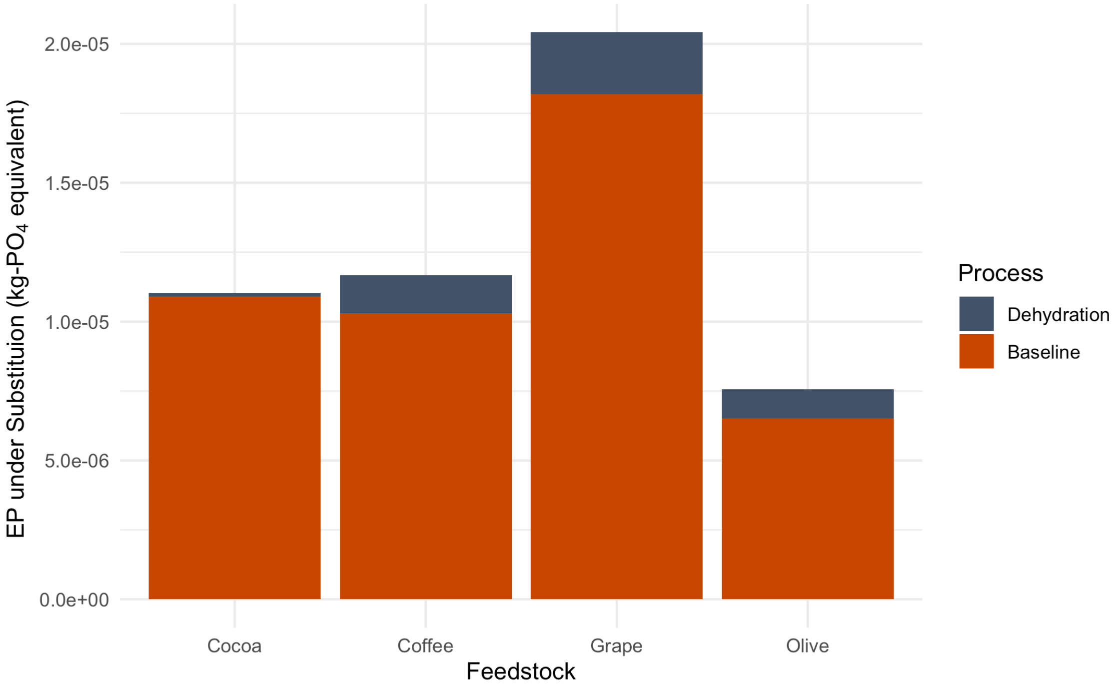

Figure 26. Eutrophication Potential with Dehydration Process (Substitution for N Fertilizer). Red bars indicate the baseline results with blue indicating the additional impacts incurred when adding dehydration to the process. The inclusion of dehydration does not change the order of EP impact for the substitution method.

Finally, Figure 26 shows the eutrophication potential with the dehydration process under substitution for N fertilizer. Higher EP impact from the dehydration of coffee cherries makes them less preferable than cocoa husks, while in the baseline scenario it was the more preferable.

Overall, adding the additional process of dehydration did not change any of the baseline results when using economic allocation. When calculating the impacts using the substitution method and assuming a nitrogen fertilizer substitution, the feedstock with the lowest greenhouse gas emissions did change from coffee cherries to cocoa husks.

5.4 Summary of Results

Generally, the scenario analysis for the substitution method has more scenarios differentiated, including the top two choices for three of the four impact categories. Additionally, the worst choice was also differentiated.

Despite this differentiation, the substitution method highlights how specifics of each scenario matter. In no case did both alternative uses for a feedstock rank as the two least impactful options. That means that no individual feedstock was differentiated from all others. Thus, the specific use for a feedstock is a significant determinant of whether the option is the least impactful.

Discussion

1. Main findings

Through our case study, we were not able to determine conclusively which waste feedstock has the lowest impacts. Consequently, we were not able to recommend the most environmental sourcing option to Apeel. However, we were able to generate conclusions that we believe can help inform any organization considering circular economy as a sustainability strategy:

- **Even feedstocks that are generally regarded as waste may have an alternative use.** We began our research with two feedstocks that Apeel had initially categorized as waste, however we found that all four feedstocks could be used as inputs in multiple other industries. Like Apeel, another industry may be using a particular "waste" feedstock to be less impactful based on the assumption that the material would be discarded. It is therefore important that organizations conduct adequate due diligence, to ensure that a waste is indeed a waste.
- **Choice of methodology by the analyst affects the decision outcome**. While the choice of methodology may appear arbitrary or influenced by situational details (such as data availability), our analysis shows that the choice of methodology may be a differentiating factor in deciding what waste feedstock has the lowest impact. This highlights that a feedstock may not inherently be more environmentally friendly, it may be a product of the methodology and specific scenario the analyst is choosing.

From these conclusions, we recommend organizations / analysts approaching a similar question always do the following:

- **Set specific environmental goals.** The feedstock with the lowest environmental impacts differed across impact categories for both methodologies. While there do exist weighting schemes to combine all impact categories into a single metric, none have reached a general consensus as being the best of even a standard (Huppes et al., 2011). It is therefore crucial for companies to approach a sourcing decision with specific goals and objectives in mind. These could relate to larger social or environmental issues the company values, or that are part of an overall strategy.
- **Identify specific potential sources in addition to specific feedstocks.** Within the economic allocation methodology, changes in market prices for primary products result in several feedstocks having overlapping impact ranges. This means that even holding the methodology and impact category constant, there may not be a clear answer as to which feedstock has the lowest environmental impact. On the other hand, our scenario analysis with the substitution methodology revealed that the feedstock with the lowest baseline environmental impact was always the best choice regardless of the change in ratio (except for eutrophication potential in which it was undifferentiated from one feedstock). Additional work is needed to test if this finding was a result of the methodology, or the result of the assumptions and analysis choices we made. Finally, the inclusion (or exclusion) or processes will affect the overall results. The dehydration scenarios showed how the inclusion of an additional process

can change the ranking of feedstocks by making one become more impactful than the other.

Together these conclusions highlight the need for an organization and/or analyst to approach an environmental impact assessment with predetermined goals and priorities in mind. The results also highlight how using only one methodology may result in a company overlooking information needed to make an optimal choice.

2. Limitations

The results generated from our case study were calculated under assumptions that if relaxed, could alter the results and ultimate recommendations. By assuming partial equilibrium, we do not consider any market changes that may occur as a result of Apeel's sourcing decisions. While this assumption may be reasonable for a company of Apeel's size, it will not always be true. If a larger company were to source large amounts of waste, the additional revenue the waste producer would receive might incentivize them to expand their operations. The increase in negative environmental impacts that result from the expansion could exceed the reduction of impacts generated from sourcing the waste. The result could be a net increase in environmental impacts, directly contradicting the motivation to source waste. Similarly, a business may be able to source the waste at a cheaper price than with virgin alternatives. This cheaper price may push the business to increase production, causing a similar net increase in environmental impacts despite transitioning to a more circular supply chain.

A second major assumption underlying our analysis was that all four feedstock choices would result in a reduction in environmental impacts compared to whatever material Apeel sources now. Our research did not compare results with Apeel's current input material. Therefore, we cannot definitively state whether sourcing a waste feedstock would make Apeel more sustainable. If Apeel already sources an extremely environmentally friendly substance, it may be the case that sourcing a waste may not result in a net reduction of environmentally harmful impacts.

Even if Apeel compares our results internally and determines that waste feedstocks overall have a lower environmental footprint, there are two additional points that we have not resolved but believe warrant discussion. The first is a temporal consideration. Within the substitution method part of the environmental impact is derived from the decisions and actions of other stakeholders. If a business does switch to the feedstock, these exists a question of whether it should continue counting the environmental burden of diverting the feedstock from an alternative indefinitely.

The second point is to consider is the fate of the material currently being sourced by Apeel. While our research has focused on all the possible fates of the waste product, the same question can be asked of the material currently being sourced. Regardless of whether the material becomes an input to another product or is discarded, there will be some environmental impact. This impact would come as a consequence of a sourcing decision, and in line with substitution's focus on net environmental impacts could be incorporated into the calculation.

While our project did not specifically analyze these questions in the context of our case study, we think they are relevant for companies and analysts to consider and also represent areas that could be explored in future studies.

Lastly, because our quantitative analysis relied on data derived from literature review, we were limited by what data was publicly available. The scenario analysis using our substitution ratio illustrates this - lacking data, we chose to change the substitution by +/-10%. Higher data resolution on the nutrient content of olive pomace resulted in a scenario analysis by approximately +/-30%, suggesting that the 10% assumption may not be realistic depending on the scenario.

3. How our results can further guide organizations

Despite our limitations, we believe our results indicate that the substitution method can be a more reliable way to capture all possible impacts of the decision to source waste, and help organizations avoid the possible pitfalls of transitioning to a circular economy. However, we recognize that it is difficult to recommend that an organization measure its own impacts based in part on a completely separate entity's action. Therefore, below we provide some initial screening criteria to help firms determine if an analysis similar to our substitution method is the best way to capture the environmental impacts of their sourcing decision. These may be thought of as questions to help organizations think critically about considering scenarios similar to what we analyzed with our substitution method. Our tool can then be used to take companies step by step through the data collection and calculations needed to perform the quantitative analysis.

3.1 Scale

The size of the company, or the amount of material necessary to create a product, may change our assumption of partial equilibrium. It is therefore important that larger organizations consider the consequences of market movements if the waste they source becomes valorized. If a company determines that their needs might result in changes in production, either within their supply chain or the sourcing organizations, we recommend using a substitution or systems expansion perspective when quantifying potential impacts.

3.2 Likelihood of substitution

In all our substitution analyses, we assumed that the actor that was initially using the waste feedstock, prior to Apeel's sourcing decision, would replace the lost source with a virgin material. Whether or not this actually happens depends on the existing linkages between industries. For example, much of the research conducted on alternative uses for coffee cherries, such as animal feed or compost, occurred in rural regions of developing countries. In fact, the research into coffee cherries as animal feed was partially motivated by the fact that farmers in this particular region of Mexico had restricted access to processed maize products but were adjacent to coffee producing regions (Pedraza-Beltrán et al., 2012). A farmer in this type of environment may not have easy access to a large supplier with different types of animal feed or fertilizer. Therefore, if their current source for this material, i.e. the coffee cherries, were diverted by Apeel, they may not replace it with a chemical or commercial alternative and rather work with another nearby producer, or even reduce their production. In this case, the environmental impacts of Apeel's diversion may not be as high as our analyses suggest (although the social impacts may still be an important consideration).

The linkages between producers and access to alternative sourcing options may vary by geographic region, but also may vary depending on the size of the producers and the size of surrounding producers they may rely on. Additionally, regional infrastructure could dictate a producer's access to suppliers located at larger distances. We therefore recommend companies' research the regional producing trends once they have pinpointed specific sources, focusing on interconnectedness between local producers and general access to the market.

4. How our results reflect on LCA

The substitution method used in this project essentially tackles consequential LCA (CLCA) with a process-based (attributional) LCA (ALCA) method. CLCA includes processes both inside and outside the system boundary to capture the processes indirectly affected by the studied product/service. The justification behind CLCA is the potential for a change in demand of other products/services as a consequence of the studied system (Earles & Halog, 2009).

Though CLCA is considered to capture the "true environmental impacts" of a production/service, it is notoriously hard to apply since it will incorporate economic models and require a significant amount of data. This project, by introducing a "common substitution system," simplifies the process into two separate product systems, which can be analyzed only by ALCA. The substitution method significantly reduces the data intensity compared to CLCA, by sacrificing the precision of the results.

We feel that it is important that all organizations motivated to make environmental changes to their systems have the tools and data they need to do it. In undertaking this project from the point of view of a small to medium-size company, like Apeel Sciences, we found there to be substantial barriers to accessing the necessary information for those outside the academic community. We hope future work can build on our research to forge stronger collaborations between producers and those generating LCA data and tools. Accessibility is key if we hope to engage actors across industries and sectors in the fight against climate change and environmental degradation.

5. Conclusion

Overall, these results help show that it is beneficial for companies to try and build a more holistic understanding of their sourcing decisions rather than just rely on specific methodologies to quantify the results. Economic allocation does not capture impacts outside the immediate system of interest, which we demonstrate can be as large if not larger than those generated by the immediate system. With our substitution method we show an example of how one organization's decision may influence a decision by another firm that can inflate environmental impacts. Therefore, it's important for businesses to consider the impacts of their sourcing decisions more holistically by looking at what will replace the waste when taking a feedstock away from another use, and we hope our framework and tool serve as a starting point to do so.

Appendix A – Detailed LCA Discussion

In process based LCA, which is implemented by this project, analyses are done by using linear algebra and a series of matrices. These matrices are commonly referred to as "A (the technology matrix)," "B (the environmental matrix)," and "C (the impact matrix)." The A matrix indicates the quantities of input processes that are used in producing the functional unit. The B matrix contains the environmental emissions caused by each particular input process. The C matrix converts the emissions to a set of environmental impacts.

While our analysis did not reach the granularity of inputs that many LCAs reach, it did utilize those that did, and our calculations themselves do follow the same conceptual underpinning. For example, in many LCAs we sourced, diesel was an input to their A matrix, and the impacts from diesel a feature in their B matrix. However, in our matrices diesel is not directly referenced. Rather, we included the process that consumes diesel as an input within our A matrix and the LCA's report of environmental impacts caused by the process as the B matrix input. Therefore diesel, and all other inputs that were used in each LCA, were embedded within our calculation.

Taking grape pomace as an example, Figure 27 shows the generic system of this project. For this system, there are many equivalent ways to construct the A and B matrices, depending on the data availability. Table 6 shows the matrices for this generic system. The direct inputs to the grape pomace system (figure 27) are not explicitly included within our matrices but are embedded within the processes that were included (table 6).

Note that in this project, instead of an actual grape pomace "production" process, an allocated process from grape production (under economic allocation) or a fertilizer production process (under substitution) is used. Hence, the calculation framework still follows the process-based LCA approach.

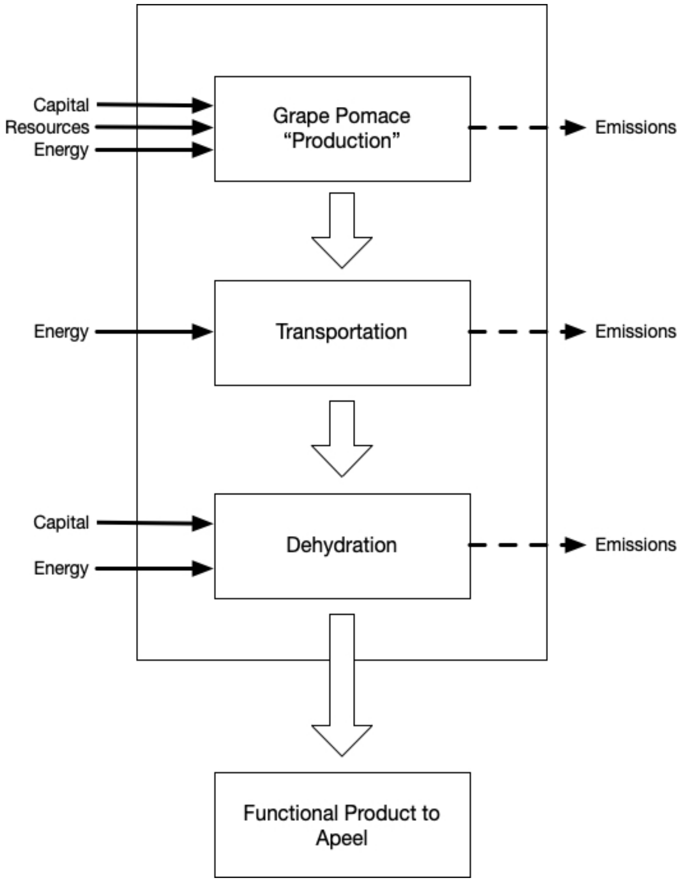

Figure 27. Generic system for grape pomace. Data for the production process was derived from previous LCAs on the wine making industry. While we included dehydration as part of our scenario analysis, we did not include any transportation beyond what was already included in the data from literature.

Table 6. Example matrices for analysis. Example A matrix and B matrix that can be developed from our calculations.

<table>
<tr><th colspan="5">A Matrix</th></tr>
<tr><td></td><td>Functional Unit</td><td>GP "Production"</td><td>Transportation</td><td>Dehydration</td></tr>
<tr><td>Functional Unit</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>GP "Production"</td><td>a1</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>Transportation</td><td>a2</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>Dehydration</td><td>a3</td><td>0</td><td>0</td><td>0</td></tr>
<tr><th colspan="5">B Matrix</th></tr>
<tr><td></td><td>Functional Unit</td><td>GP "Production"</td><td>Transportation</td><td>Dehydration</td></tr>
<tr><td>Emission 1</td><td>0</td><td colspan="3" rowspan="6">Values</td></tr>
<tr><td>Emission 2</td><td>0</td></tr>
<tr><td>Emission 3</td><td>0</td></tr>
<tr><td>Emission 4</td><td>0</td></tr>
<tr><td>Emission 5</td><td>0</td></tr>
<tr><td>…</td><td>0</td></tr>
</table>

Appendix B – Functional Equivalencies

Table 7. Functional Equivalencies for each Substitution Scenario. This table displays the function a waste product served, followed by what product is being substituted into use. Finally, it displays the amount of the substitute product that is equivalent to 1 kg of the waste product. These values form the baseline for each tested scenario.

Scenario	Functional Component of Waste	Substituted Product	Equivalent Substitute Product to 1 kg Waste by Specified Function (kg)
Cocoa for Biofuel	Energy Content	Biofuel	4.94E-01
Cocoa for Fertilizer	Nitrogen Content	Fertilizer	0.025
Coffee for Animal Feed	Caloric Content	Animal Feed	1
Coffee for Fertilizer	Nitrogen Content	Fertilizer	0.024
Grape for Animal Feed	Caloric Content	Animal Feed	1.023
Grape for Fertilizer	Nitrogen Content	Fertilizer	0.042
Olive for Secondary Oil	Oil Content	Secondary Oil	1.42
Olive for Fertilizer	Nitrogen Content	Fertilizer	0.015

Appendix C – Baseline Results

Table 8. Full Baseline Results. Baseline results for each of the four impact categories are displayed for each scenario. The scenarios are sorted first by the feedstock and then by the specific scenario being considered.

Feedstock	Scenario	GHG (kg of CO_2e per kg waste)	AP (kg SO_2e per kg waste)	EP (kg PO_4e per kg waste)	Land Use (m^2 of arable land per kg waste)
Cocoa	Biofuel	5.91E-02	1.53E-04	4.83E-06	4.10E-04
Cocoa	Fertilizer	2.88E-01	1.28E-03	1.09E-05	1.67E-02
Cocoa	Economic	7.02E-02	8.93E-04	1.50E-03	1.33E-02
Coffee	Animal Feed	5.95E-01	5.31E-03	3.56E-04	7.37E-01
Coffee	Fertilizer	2.74E-01	1.22E-03	1.03E-05	1.59E-02
Coffee	Economic	9.63E-02	2.11E-04	2.77E-04	7.30E-01
Grape	Animal Feed	2.93E-01	1.07E-02	1.74E-04	1.15E+00
Grape	Fertilizer	4.84E-01	2.15E-03	1.82E-05	2.81E-02
Grape	Economic	1.69E-01	7.62E-04	5.79E-04	8.36E-02
Olive	2nd Oil	2.94E-01	2.86E-03	2.63E-04	6.56E-01
Olive	Fertilizer	1.73E-01	7.66E-04	6.52E-06	1.00E-02
Olive	Economic	2.36E-02	1.08E-01	6.88E-02	1.35E-01

Appendix D – All Results

Table 9. Full Scenario Results. Baseline and high and low bound results (for all four impact categories) are displayed for each specific scenario. The results are sorted based first on the feedstock, then by the specific scenario, and finally by baseline, high or low bound.

Feedstock	Scenario	Baseline, High or Low Bound	GHG (kg of CO_2e per kg waste)	AP (kg SO_2e per kg waste)	EP (kg PO_4e per kg waste)	Land Use (m^2 of arable land per kg waste)
Cocoa	Biofuel	Baseline	5.91E-02	1.53E-04	4.83E-06	4.10E-04
Cocoa	Biofuel	High Bound	6.50E-02	1.68E-04	5.32E-06	4.51E-04
Cocoa	Biofuel	Low Bound	5.32E-02	1.37E-04	4.35E-06	3.69E-04
Cocoa	Economic	Baseline	7.02E-02	8.93E-04	1.50E-03	1.33E-02
Cocoa	Economic	High Bound	1.72E-01	2.19E-03	3.68E-03	3.25E-02
Cocoa	Economic	Low Bound	5.17E-02	6.58E-04	1.10E-03	9.77E-03
Cocoa	Fertilizer	Baseline	2.88E-01	1.28E-03	1.09E-05	1.67E-02
Cocoa	Fertilizer	High Bound	3.17E-01	1.40E-03	1.19E-05	1.84E-02
Cocoa	Fertilizer	Low Bound	2.59E-01	1.15E-03	9.77E-06	1.51E-02
Coffee	Animal Feed	Baseline	5.95E-01	5.31E-03	3.56E-04	7.37E-01
Coffee	Animal Feed	High Bound	6.55E-01	5.84E-03	3.92E-04	8.11E-01
Coffee	Animal Feed	Low Bound	5.36E-01	4.78E-03	3.20E-04	6.63E-01
Coffee	Economic	Baseline	9.63E-02	2.11E-04	2.77E-04	7.30E-01
Coffee	Economic	High Bound	1.66E-01	3.63E-04	4.77E-04	1.26E+00
Coffee	Economic	Low Bound	5.07E-02	1.11E-04	1.46E-04	3.84E-01
Coffee	Fertilizer	Baseline	2.74E-01	1.22E-03	1.03E-05	1.59E-02
Coffee	Fertilizer	High Bound	3.02E-01	1.34E-03	1.14E-05	1.75E-02
Coffee	Fertilizer	Low Bound	2.47E-01	1.09E-03	9.30E-06	1.43E-02
Grape	Animal Feed	Baseline	2.93E-01	1.07E-02	1.74E-04	1.15E+00
Grape	Animal Feed	High Bound	3.22E-01	1.18E-02	1.92E-04	1.26E+00
Grape	Animal Feed	Low Bound	2.64E-01	9.65E-03	1.57E-04	1.03E+00
Grape	Economic	Baseline	1.69E-01	7.62E-04	5.79E-04	8.36E-02
Grape	Economic	High Bound	3.62E-01	1.63E-03	1.24E-03	1.79E-01
Grape	Economic	Low Bound	3.86E-02	1.74E-04	1.32E-04	1.91E-02
Grape	Fertilizer	Baseline	4.84E-01	2.15E-03	1.82E-05	2.81E-02
Grape	Fertilizer	High Bound	5.33E-01	2.36E-03	2.01E-05	3.09E-02
Grape	Fertilizer	Low Bound	4.36E-01	1.93E-03	1.64E-05	2.53E-02
Olive	2nd Oil	Baseline	2.94E-01	2.86E-03	2.63E-04	6.56E-01

Olive	2nd Oil	High Bound	3.23E-01	3.15E-03	2.90E-04	7.21E-01
Olive	2nd Oil	Low Bound	2.64E-01	2.58E-03	2.37E-04	5.90E-01
Olive	Economic	Baseline	2.36E-02	1.08E-01	6.88E-02	1.35E-01
Olive	Economic	High Bound	4.68E-02	2.14E-01	1.36E-01	2.68E-01
Olive	Economic	Low Bound	2.01E-02	9.18E-02	5.85E-02	1.15E-01
Olive	Fertilizer	Baseline	1.73E-01	7.66E-04	6.52E-06	1.00E-02
Olive	Fertilizer	High Bound	2.31E-01	1.02E-03	8.69E-06	1.34E-02
Olive	Fertilizer	Low Bound	1.23E-01	5.47E-04	4.65E-06	7.17E-03

Table 10. All Dehydration Results. Additional impacts caused by the dehydration process are displayed for each impact category and feedstock.

Feedstock	Scenario	Moisture Content (Percent)	GHG (kg of CO_2e per kg waste)	AP (kg SO_2e per kg waste)	EP (kg PO_4e per kg waste)	Land Use (m^2 of arable land per kg waste)
Grape Pomace	Lower bound	65	2.28E-02	6.72E-05	6.78E-07	2.18E-04
Grape Pomace	Upper bound	68	2.39E-02	7.03E-05	7.10E-07	2.28E-04
Olive Pomace	Lower bound	30	1.05E-02	3.10E-05	3.13E-07	1.01E-04
Olive Pomace	Upper bound	70	2.46E-02	7.24E-05	7.31E-07	2.35E-04
Cocoa Husks	Lower bound	4.6	1.62E-03	4.76E-06	4.80E-08	1.54E-05
Cocoa Husks	Upper bound	10.7	3.76E-03	1.11E-05	1.12E-07	3.59E-05
Coffee Pulp	Median	56.5	1.98E-02	5.84E-05	5.90E-07	1.90E-04

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