UNIVERSITY OF CALIFORNIA
Santa Barbara

Reducing greenhouse gas emissions through materials innovation in the apparel industry

A Group Project submitted in partial satisfaction of the requirements for the degree of Master of Environmental Science and Management for the Bren School of Environmental Science & Management

by:

Giovanna Davila
Camille Herrera
Derek Hunter
Caitlin Martin
Bri Winkler

Committee in Charge:
Dr. Roland Geyer
Jason Maier

March 2019

Reducing greenhouse gas emissions through materials innovation in the apparel industry

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.

Giovanna Davila

Camille Herrera

Derek Hunter

Caitlin Martin

Bri Winkler

The Bren School of Environmental Science & Management produces professionals with unrivaled training in environmental science and management who will devote their unique skills to the diagnosis, assessment, mitigation, prevention, and remedy of the environmental problems of today and the future. A guiding principal of the School is that the analysis of environmental problems requires quantitative training in more than one discipline and an awareness of the physical, biological, social, political, and economic consequences that arise from scientific or technological decisions.

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. Roland Geyer

Acknowledgements

The team would like to extend gratitude to our faculty advisor, Dr. Roland Geyer, and our PhD mentor, Jason Maier, for their support and guidance throughout this project.

Faculty Advisor
Dr. Roland Geyer

PhD Mentor
Jason Maier

Clients
Elissa Foster
Elena Egorova
Steph Karba

External Advisor
Dr. Sangwon Suh

Other External Advisors
Dr. Lisa Leombruni
Patagonia's Materials, Innovation, and Development Team
Sustainable Apparel Coalition

Table of Contents

List of Figures

List of Tables

List of Abbreviations and Acronyms

CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DB eq	Dichlorobenzene equivalent
DMT	Dimethyl terephthalate
EP&L	Environmental Profit & Loss
EPTFE	Expanded polytetrafluoroethylene
EU	European Union
GDP	Gross domestic product
GHG	Greenhouse gas emissions
GWP	Global warming potential
Higg MSI	Sustainable Apparel Coalition's Higg Material Sustainability Index
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
kWh	Kilowatt hour
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
NRDC	National Resource Defense Council
PaCT	Partnership for Cleaner Textiles
PBDE	Pentabromodiphenyl ether
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoates
PFOS	Perfluorooctane sulphonate
PLM	Patagonia's Project Line Management System
PU	Polyurethane
PSI	Product swap index
SAC	Sustainable Apparel Coalition
SBT	Science Based Targets
SBTi	Science Based Targets Initiative
TBT	Tributyltin
Ton	US ton
Tonne	Metric ton
TPU	Themoplastic polyurethane
UNFCCC	United Nations Framework Convention on Climate Change
WSI	Water stress index

Abstract

The global apparel industry is notoriously resource intensive and polluting. In response to the imminent threat of climate change, apparel companies are focusing significant effort on reducing their carbon footprints by setting aggressive greenhouse gas (GHG) emission reduction targets. Patagonia is interested in exploring the feasibility of these goals, as well as a realistic pathway to reduce absolute GHG emissions. Through their company carbon footprint assessment, Patagonia found that 85% of its GHG emissions come from textile production. To address this issue, our project analyzed potential GHG emission reductions from adopting alternative material and dye technologies, which affect two stages of the textile production process. The objectives of this project were to: 1) quantify GHG emission reductions through the adoption of new materials and dyes, 2) develop material and dye recommendations to reduce Patagonia's GHG emissions by 2035, and 3) assess corporate GHG emission reduction methods and goals. We found that Patagonia can reduce GHG emissions compared to baseline levels through implementing alternative materials and dyes; however, these reductions cannot compete with the emissions associated with company growth and are not large enough to meet GHG reduction goals alone. This speaks to the inherent tension between company growth and absolute GHG emission reductions for the entire apparel industry and all facets of the economy.

Executive Summary

Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement aims to maintain global temperature rise below 1.5°C compared to pre-industrial levels. National GHG emission commitments are being set to achieve this goal; and as large contributors, companies play a critical role in reaching these targets, especially resource-intensive and polluting companies, like those in the apparel industry. A Quantis study commissioned by ClimateWorks found that the apparel industry accounts for 6.7% of global carbon emissions. In response, apparel companies are focusing on reducing their carbon footprints by setting aggressive GHG reduction goals, such as carbon neutrality and science-based targets.

Patagonia is interested in the feasibility of setting a GHG target for the company, as well as a realistic pathway to achieve those GHG reductions. Patagonia conducted a company-wide carbon footprint assessment for fiscal year 2017 (May 1, 2016-April 30, 2017), which found that textile production accounts for 85% of total company GHG emissions. In contrast, product manufacturing, including cutting, sewing and formation of the final product, only represents 1.4% of Patagonia's total carbon footprint (SGS Consulting, 2018).

Objectives

This project analyzed textile production, the most GHG intensive stage of garment manufacturing. The primary project objectives were to:

1. Quantify GHG emission reductions through the adoption of alternative materials and dyes.
2. Develop material and dye recommendations to reduce Patagonia's GHG emissions by 2035.
3. Assess corporate GHG emission reduction methods and goals.

In order to reach these objectives, the team answered the following research questions:

1. *What are the GHG intensities of alternative materials and dyes?*
2. *How much can Patagonia reduce its GHG emissions by implementing less impactful materials and dyes?*
3. *How can a growing company like Patagonia feasibly reduce absolute GHG emissions?*

Significance

According to the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report, climate change will lead to a significantly high risk of "severe, widespread and irreversible impacts globally," without increased mitigation efforts (IPCC, 2014). Mitigation efforts should be undertaken not just by nations, but also industry and the companies within them. For many apparel companies, textile production is the greatest portion of company GHG emissions. There are opportunities to address these emissions during the product design phase by using less GHG intensive materials and dyes.

Methods

Research Question 1: What are the GHG intensities of alternative materials and dyes?

A literature review evaluated GHG intensities expressed as kilograms of carbon dioxide equivalent per kilogram of material (kg CO_2e/kg material) of existing material and dye processes compared to alternative methods. GHG intensities for conventional technologies were largely given by Patagonia, but other values were found in the Higg MSI, a database quantifying the environmental impacts of the five stages of textile production. To identify values for alternative technologies, a combination of Higg MSI, scientific literature, and supplier data were used. The level of scientific rigor varied across data sources, and a data quality ranking system was created, serving as a reference point for quality assurance through the project and to inform product recommendations.

Research Question 2: How much can Patagonia reduce its GHG emissions by implementing less impactful materials and dyes?

Patagonia provided a product dataset, which identified GHG intensities for each stage of the textile production process. Fiscal year 2017 was analyzed to align with Patagonia's Carbon Footprint Report timeframe. Our team in collaboration with Patagonia identified opportunities for material and dye substitutions within the product portfolio and crafted four scenarios that grouped categories of product swaps. Across scenarios, there were 61 substitutions, referred to as product swaps, which switched the GHG intensity of the conventional method with the alternative technology. The product swaps fell into three timeframes, near-term (2019-2024), mid-term (2025-2029), and long-term (2030-2034), based on Patagonia's scheduled product changes and the technical feasibility of the materials and dyes. A naming protocol was developed to aid in the organization of these changes called the Product Swap Index, or PSI.

A series of filters were applied to the entire dataset of over 150,000 lines of product information to swap existing GHG intensities with alternative technologies. First, all product components for each PSI were identified. Next, the stage of material process, either raw material production or dye, was specified. GHG emissions for each product swap were calculated using the GHG intensities and the mass of the product components under each product swap, resulting in the GHG emissions per product for conventional and alternative technologies. Using this information, the GHG emissions savings per product swap were calculated.

Research Questions 3. How can a growing company like Patagonia feasibly reduce its absolute GHG emissions?

Growth was analyzed over the 15-year timeframe by increasing the mass of products affected by each product swap with an assumed 10% growth rate. Business-as-usual product GHG emissions per year were calculated and compared to GHG emissions per year after product swap implementation.

Before calculating emission savings from Patagonia's proposed scenarios, product dependencies were identified, as conflicts existed between some product swaps. This prevented double counting GHG savings and kept track of the cascading impacts of earlier product swaps on those occurring later. Dependencies fell into three categories: preceding, competing, and material-dye conflicts.

Determining which product swaps to implement was based on aggregated GHG savings per product swap from 2020-2034. Once dependencies were identified, it was possible to calculate the proposed scenarios' emissions savings without double counting any savings. As a thought experiment, the team found that maintaining 2019 emissions levels through the end of the timeframe analyzed, 2020-2034, would require limiting annual growth to an amount that could be balanced by the implementation of the product swaps analyzed in this report.

Results and Recommendations

The results include least impactful GHG intensities, product change analysis, growth and GHG emissions analysis, and product change recommendations.

From the values identified through the literature review, the GHG intensities were compared to determine if alternative methods were less GHG intensive than existing methods. The results show that virgin materials have the highest GHG intensities across all categories. For most categories, bio-based sources have the second highest GHG intensities. When available, recycled raw material sources have the lowest GHG intensities. Recycled cotton, duck down insulation, nylon, and PET show the greatest emissions reductions compared to virgin, while bio-based polyurethane (PU) and thermoplastic polyurethane (TPU) show emissions reductions compared to virgin.

Solution dye, and Dye Technologies A, B, C, and D had lower GHG intensities than conventional dyes. Some of the dye technologies can only be used on certain material types, such as natural dye for natural materials and solution dye for synthetic materials. The feasibility of product application, as well as GHG intensity reduction, were considered in the analysis. Out of all 61 product swaps, 55 technologies decreased GHG intensities and 10 increased.

Using the change in product swap GHG intensities and dependencies, the team analyzed Patagonia's four scenarios. A recommended strategy of product swap combinations that reduced the greatest emissions was also crafted. Scenario 1 included near-term changes. Scenarios 2-4 built upon GHG emission reductions achieved from product swaps implemented in Scenario 1. The counterfactual emitted a total of about 5,660,000 tonnes CO_2e emissions from 2017-2035.

Under Scenario 1 product changes, emissions were less than the counterfactual. Scenario 1 emitted about 5,012,000 tonnes CO_2e. Scenario 2 included product swaps impacting large category shifts, such as changing the dye technology for a large category. Building on the near-term product changes in Scenario 1, Scenario 2 product swaps reduced slightly more emissions, for total emissions of about 4,933,000 tonnes CO_2e from 2017-2035. Scenario 3 included bio-based material product swaps. Building upon Scenario 1, Scenario 3 product swap savings were minimal. Scenario 3 emitted about 5,000,000 tonnes CO_2e from 2017-2035. Scenario 4 product swaps included large dye technology changes in the mid and long term. Building on Scenario 1, Scenario 4 product changes reduced the most emissions, for total emissions of about 4,826,000 tonnes CO_2e.

The recommended strategy of product swaps included product swaps across all three time periods, including changes to smaller collections of product, as well as large category shifts, to reduce overall portfolio GHG emissions. The reduction of total GHG emissions from about 5,660,000 tonnes CO_2e in the counterfactual to about 4,774,000 tonnes CO_2e under the recommended strategy achieved about a 15% reduction in overall GHG emissions.

As a thought experiment, Patagonia was curious to see the growth rate that would hold current emissions levels constant at the end of the 15-year timeframe. This analysis found that an annual growth rate of 1.58% resulted in 2034 emissions equaling 2019 levels.

Discussion

The difficulty in achieving net reductions in GHG emissions lies in the tension between having economic success defined by annual growth and the limits of reducing GHG emissions through technological innovation, provided here by using less impactful technologies. Decreasing the rate of growth will slow the amount of GHG emissions over time, but will ultimately still lead to increases in GHG emissions. Even limiting company growth will only keep GHG emissions constant at the level when the growth rate was capped, but will not lead to reductions.

To counteract some of the GHG emissions impact associated with company growth, other business models can be explored, like reuse and rental programs. Reuse programs assume reduced emissions through garment life extension from a purchased second life, leading to reduced new product purchases. Patagonia's Worn Wear program, where gently used products are resold at a discounted price, is a reuse program. Rental programs assume reduced emissions through repeated reuse by many customers, thereby avoiding emissions associated with virgin product customers would have otherwise purchased. Due to the challenge company growth poses for emissions reduction, companies will need to adopt multiple strategies and programs to successfully reach ambitious GHG emission reduction targets.

Conclusion

This analysis demonstrated that the product design phase provides an opportunity to leverage alternative materials and dyes to proactively reduce apparel product environmental impacts. However, tension between company growth and the GHG savings rate is a challenge to reaching net GHG emission reductions for any one mitigation approach. Patagonia can significantly reduce its GHG emissions by implementing alternative materials and dyes, but these efforts must be supplemented by other strategies to meet aggressive GHG reduction targets, such as science-based targets and carbon neutrality. Inherent limits exist in the corporate sector because annual growth defines economic success, which counteracts GHG emissions reductions through product design. Patagonia, the apparel industry, and nearly all facets of the economy face this contention. Regardless, addressing textile production is critical as it accounts for 85% of Patagonia's overall GHG emissions. Reducing GHG emissions from textile production through innovative material and dye changes or other approaches, are essential steps for the apparel industry to be part of the climate change solution.

1.0 Project Objectives & Significance

On behalf of Patagonia Inc., the team analyzed the process of textile production, the most greenhouse gas (GHG) intensive stage of garment manufacturing. The primary objectives were to:

1. Quantify GHG emission reductions through the adoption of new material and dye technologies.
2. Develop material and dye recommendations to reduce Patagonia's GHG emissions by 2035.
3. Assess corporate GHG emission reduction methods and goals.

The team first identified GHG intensities for alternative materials and dyes in order to compare the new technologies to their traditional counterparts. These new technologies include, but are not limited to, bio-based polyester, bio-based nylon, recycled polyester, post-consumer recycled nylon, and solution dye. After applying the new technologies to a list of product changes, the team calculated the extent to which Patagonia can reduce its GHG emissions through the use of less impactful materials and dyes in its products.

In addition to the prescribed scenarios developed in collaboration with Patagonia, the team recommended specific product changes, implemented from 2020-2035, that achieved significant GHG emissions reductions. The analysis also incorporated assumed company growth as an illustration to examine how a growing company can continue to reduce overall GHG emissions.

Finally, the team assessed the applicability and feasibility of ambitious corporate GHG emission reduction programs for a growing apparel company. A literature review provided perspective on corporate emission reduction plans, including carbon neutrality and science-based targets.

As part of the original proposal for this project, the team also conducted research on current pricing schemes to inform how Patagonia may set an internal price on carbon and a region-specific price on water, dependent on water scarcity and risk.

This analysis answers the three following research questions:

1. *What are the GHG intensities of alternative materials and dyes?*
2. *How much can Patagonia reduce its GHG emissions by implementing less impactful materials and dyes?*
3. *How can a growing company like Patagonia feasibly reduce its absolute GHG emissions?*

According to the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report, climate change will lead to a significantly high risk of "severe, widespread and irreversible impacts globally," without increased mitigation efforts (IPCC 2014). Mitigation efforts can be undertaken not just by nations, but also industries and the companies within them. In the apparel industry, there exists an opportunity for companies to reduce GHG emissions from their largest impact: textile production. There are alternative material and dye technologies with lower impacts than conventional technologies, and leveraging this information during product design can reduce emissions.

2.0 Background

2.1 Industry Landscape

The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement aims to maintain global temperature rise below 1.5°C compared to pre-industrial levels. National GHG emission commitments are being set to achieve this goal; and as large contributors, companies play a critical role in reaching these targets. The Science Based Targets Initiative (SBTi), a collaboration between the World Resources Institute, World Wildlife Fund for Nature, UN Global Compact, and CDP (formerly the Carbon Disclosure Project), developed guidelines for setting science-based targets (SBT). These guidelines include industry specific targets to help ensure corporate carbon reduction goals are robust enough to meet the 1.5°C goal.

The apparel industry is leading the way in setting ambitious carbon reduction targets. Some apparel companies have committed to the SBTi and many others are exploring ways to achieve carbon neutrality or net negative. However, there are many uncertainties and challenges in setting aggressive yet achievable goals. First, it is difficult to quantify and track supply chains and raw materials, which contribute to the majority of GHG emissions. Also, most companies have limited control over Scope 3 emissions, especially the use phase of their product or service. Lastly, incorporating company growth has inherent challenges as it requires accurate forecasting and a realistic plan of achievable reductions.

As of March 2019, SBTi has not published prescriptive apparel sector guidelines for setting Scope 3 targets, thereby lending to greater uncertainty in target setting for an already ambiguous emissions category. According to the Greenhouse Gas Protocol Corporate Standard, Scope 3 emissions refer to indirect GHG emissions that occur throughout a company's supply chain

(Schmitz et al., 2000). Based on the SBTs already set by other leading apparel companies, such as Kering and Levi Strauss & Co., the apparel industry generally aims to reduce Scope 3 emissions 40% by the year 2050.

Patagonia is a leader in corporate sustainability, yet they have not set public facing GHG reduction targets. Before committing to these goals, the company wants to evaluate the feasibility of achieving these challenging targets.

2.2 Patagonia, Inc.

Patagonia conducted a company-wide carbon footprint assessment for fiscal year 2017 (May 1, 2016-April 30, 2017). This study found that textile production accounts for 85% of the company's total GHG emissions. In contrast, product manufacturing, including cutting, sewing and formation of the final product, only represents 1.4% of Patagonia's total carbon footprint (SGS Consulting, 2018).

Patagonia's Materials, Innovation and Development team is largely responsible for managing the environmental impacts associated with manufacturing and searches for technologies to reduce the environmental impacts of textile production. In response to the carbon footprint results, Patagonia's Materials team wanted to explore to what extent using new and alternative material technologies would reduce the company's overall GHG emissions.

Under the methodology of the Sustainable Apparel Coalition's (SAC) Higg Material Sustainability Index (Higg MSI), there are five main stages of textile production per garment:

(Sustainable Apparel Coalition, 2016)

The Higg MSI is a cradle-to-gate material scoring tool that uses life cycle assessment methodology to help textile, apparel, and footwear companies measure and score the environmental impacts of their products in a systematic and standardized way (Sustainable Apparel Coalition, 2016). Developed and managed by the SAC, the Higg MSI offers an industry-wide standard to report and track environmental impacts and is used by companies internationally, including Patagonia. The

Higg MSI has been instrumental in addressing the inherent difficulties associated with quantifying the environmental impacts of the apparel industry supply chain.

The innovative technologies analyzed in this project provide alternatives to raw material sources (stage 1) and dyeing and coloration (stage 5). These two stages in material manufacturing were analyzed since the majority of innovative technologies available in the market today address raw materials and dyeing techniques. Additionally, apparel companies have the most control over these two stages and have limited data on the environmental impacts of yarn formation, textile formation, and finishing (stages 2-4). According to a recent study of the global apparel industry conducted by Quantis, dyeing, yarn formation, and raw material production are the most energy-intensive processes and drive the industry's overall environmental impact (Quantis, 2018). While yarn formation is associated with larger GHG emissions than raw material production, apparel companies generally have less control over the emissions from this process.

A complex issue for all companies trying to reduce GHG emissions is the tension between company growth and emission reductions. A business that sells more products or provides more services will have larger GHG emissions unless the rate of emission reductions overtakes growth. While material innovations decrease Patagonia's carbon footprint, annual growth will lead to net growth in GHG emissions. Incorporating assumed company growth with the adoption of innovative technologies is thus incredibly important for understanding what realistic GHG reduction goals Patagonia can achieve.

Across scientific literature, studies analyzing environmental impacts of material and dye technologies consider a wide variety of environmental impact categories. For instance, life cycle assessments (LCA) for recycled and reused textiles, on average, consider fourteen different impact categories, including but not limited to global warming potential (GWP), energy use, acidification, eutrophication, water use/depletion, ecotoxicity, and non-renewable energy use, among others (Sandin & Peters, 2018). Limiting research to GHG emissions excludes potential opportunities to reduce chemical toxicity, waste, or any of the aforementioned impacts associated with textile production. While all impacts of the apparel industry are undoubtedly important, this study focuses on GHG emissions of raw material and dye technologies, and thus others are considered outside the scope of the project. Moreover, water was left out of this analysis due to the lack of data on water impacts in the apparel industry.

The project's focus on GHG emissions parallels the impact categories most studied within scientific literature. According to a study conducted by Allwood et al., GHG emissions represents one of the most significant issues in the global textile industry (Allwood, J.M., Laursen, S.E., Malvido de Rodriguez, C., Bocken, 2004). Additionally, this follows trends in the global apparel industry toward setting corporate GHG reduction goals (Sandin & Peters, 2018). Since the project examined environmental impacts through the lens of SBTs, which focus on GHG emissions reductions, the analysis focused exclusively on that. Most importantly, focusing on GHG emission reductions aligns with Patagonia's larger goals and business strategy.

The following sections will provide background on categories of alternative material and dye technologies and will highlight the environmental benefits they provide compared to traditional methods.

2.3 Literature Review

2.3.1 Science-Based Targets

Several methodologies exist as frameworks for companies to use in their strategic planning for GHG emission reductions, including science-based targets (SBT). The Science Based Targets Initiative (SBTi), a collaboration between the World Resources Institute, World Wildlife Fund for Nature, UN Global Compact, and CDP, developed guidelines for setting SBT through examining the intersection between the Intergovernmental Panel on Climate Change's (IPCC) goals and company responsibility in reducing GHG emissions. The SBTi defines emission reductions as "science-based" if they align with the level of decarbonization likely to keep global warming under 1.5°C compared to pre-industrial temperatures ("What is a science-based target? | Science Based Targets," n.d.). According to the IPCC's Special Report 1.5, past and ongoing emissions are estimated to contribute 0.2°C per decade of anthropogenic global warming; therefore, to mitigate climate change, global GHG emissions must decrease by 49-72% from 2010 levels by 2050 to remain within a 2° global temperature increase.

The SBTi outlines three SBT setting approaches: sector, absolute, and economic. Each rely on a ratio of a company's total GHG emissions relative to either global or specific sector's GHG emissions. The sector-based approach is calculated by dividing the global carbon budget by sector emissions ("Methods | Science Based Targets," n.d.) Absolute-based approach takes a percentage of absolute emissions reductions and assigns them to individual companies ("Methods | Science Based Targets," n.d.). Economic-based compares the global carbon budget to global GDP (gross domestic product); a company's share of emissions can be calculated using its gross profit, with the sum of all companies' gross profits worldwide equaling global GDP ("Methods | Science Based Targets," n.d.).

Notably, carbon offsets are not an accepted method of emission reduction under SBT. Additionally, direct and indirect emission reductions (Scope 1 and 2) must meet SBTi's criteria, while Scope 3 reductions do not, because guidelines have not yet been laid out. However, companies are required to set Scope 3 targets if their emissions in that category exceed 40% of their total carbon emissions. However, these targets do not have to be "science-based".

As of November 2018, 498 companies across 44 industries have committed to SBT targets and 152 companies have set targets. This total includes four apparel companies: ASICS Corporation, Kering, Levi Strauss & Co., and Skunkfunk. Table 1 shows details of their emissions target commitments, as outlined on the SBT website.

Table 1. Stated science-based targets from four apparel companies.

	ASICS Corporation	**Kering**	**Levi Strauss & Co.**	**Skunkfunk**
Reduction Type	Absolute/ Intensity	Intensity	Absolute	Absolute
Base-year	2015	2015	2016	2017
Reduction By	2030	2025	2025	2025
Scope 1 & 2	33%	50% per unit of value added	90%	37%
Scope 3	55% per product*	40% per unit of value added*	40%	15%
Type	Public	Public	Private	Private

("Companies Taking Action | Science Based Targets," n.d.)

**There is a discrepancy between SBT-published goals and goals stated in Kering's reporting. The latter has listed reductions as 50% for Scope 1 and 2, and 40% for Scope 3, which indicates that they are absolute emission reductions, rather than intensity-based reductions.*

Despite not specializing in outdoor apparel, each company shares commonality with Patagonia. ASICS has a technical sports clothing line; Kering announced that the majority, 66%, of their environmental impacts come from raw material sourcing (Kering Integrated Report 2018, 2018);

Levi Strauss & Co., like Patagonia, is exploring innovations in plant-based fibers; and Skunkfunk incorporates recycled synthetic materials into its product line, also like Patagonia.

These apparel companies are also planning similar methods to reduce GHG emissions. To address Scope 1 emissions, they plan to increase energy efficiency at retail, office, and warehouse spaces. For Scope 2 emissions, companies are looking to purchase energy from renewable energy sources. To reduce Scope 3 emissions, all four companies are looking into raw material replacement, such as replacing virgin materials with either recycled or bio-based content. Additionally, these companies are looking to incorporate innovative dye technologies into their production.

Both Levi Strauss & Co. (Climate Action Strategy 2025, 2018) and Kering (Kering Integrated Report 2017, 2017) are leveraging outside programs to impact energy use in their supply chains. The first of these programs is the Natural Resources Defense Council's (NRDC) program called Clean by Design, which aims to improve efficiency at supplier sites. Levi's has used Clean by Design since 2012, and Kering finished its first pilot in 2016. Another program Levi's and PUMA utilize is the Partnership for Cleaner Textiles (PaCT), which offers suppliers advisory services and low-cost financing to upgrade or adjust equipment for increased energy efficiency.

Skunkfunk has a unique approach to reducing its Scope 3 emissions. Skunkfunk is "relocating its suppliers to reduce the total distance from raw materials to finished products, thus reducing upstream transportation carbon impacts by 27%" (Styles, 2018). It is unclear by which means this goal will be accomplished. For example, will the company switch to suppliers located closer to final product finishing facilities, or will it support suppliers in making the move. While an impressive example of a supply chain shift, it is important to note that Skunkfunk is a much smaller company and this kind of supply chain change is not as feasible for a larger company like Patagonia.

2.3.2 Raw Material Innovations

2.3.2.1 Bio-Based Plastic Materials

Developments in bio-based material technology have increased in recent years due to rising fossil fuel prices and goals to reduce environmental impact from traditional materials. The apparel industry has seen a shift toward the use of bio-based alternatives for materials such as polyester, nylon, and polyurethane in order to decrease environmental impacts in textile production.

Life Cycle Assessment (LCA) methodology is used to quantify the environmental impacts of bio-based materials. However, there is little consensus about the best methodology to account for carbon stored in bio-based materials (Pawelzik et al., 2013). Researchers disagree as to whether or not bio-based materials should take credit for biogenic carbon sequestered in the plant biomass. Biogenic carbon sequestration refers to the carbon taken up by plants during photosynthesis; when that plant matter is turned into a plastic, the carbon that was taken up during photosynthesis is considered an offset, or negative emissions, since that carbon was removed from the atmosphere.

The debate is over whether or not bio-based plastics should be rewarded for removing carbon when quantifying their overall GHG emissions. Two approaches are used to account for carbon storage of bio-based materials. The first method does not include biogenic carbon in analysis (Pawelzik et al., 2013). This approach argues that carbon emissions will return to the atmosphere in the future and bio-based plastics are, therefore, not actually offsetting GHG emissions (Pawelzik et al., 2013). The second approach claims a carbon sequestration benefit, and the product will see reduced GHG emissions in its analysis because of this reduction (Pawelzik et al., 2013). Most measurements of bio-based material environmental impacts use a cradle-to-gate approach rather than cradle-to-grave, which does not account for end of life and therefore favors accounting for biogenic carbon. When considering end of life of a product, GHG emissions from the sequestered carbon would return to the atmosphere.

Many agencies, including the European Commission's Lead Market Initiative, the GHG Protocol Initiative of the World Resources Institute, and the World Business Council for Sustainable Development, recommend accounting for biogenic carbon storage when examining the carbon emissions under a cradle-to-gate scenario (Pawelzik et al., 2013). ISO 14067 also recommends accounting for the removal of carbon from the atmosphere. The French Environment and Energy Management Agency, however, recommends that biogenic carbon be considered CO_2 neutral. Noting the short lifespan bio-based products of about 10-20 years, they claim the delay in radiative forcing that occurs from biogenic carbon storage is insignificant (Pawelzik et al., 2013).

Under a cradle-to-gate scenario, GHG emissions for the bio-based material are typically greater than those of the fossil fuel-based product if carbon storage is not included (Figure 1) (Wiloso, Heijungs, Huppes, & Fang, 2016). When biogenic carbon storage is accounted for, however, the bio-based material has lower GHG emissions than the fossil fuel-based product (Wiloso et al., 2016).

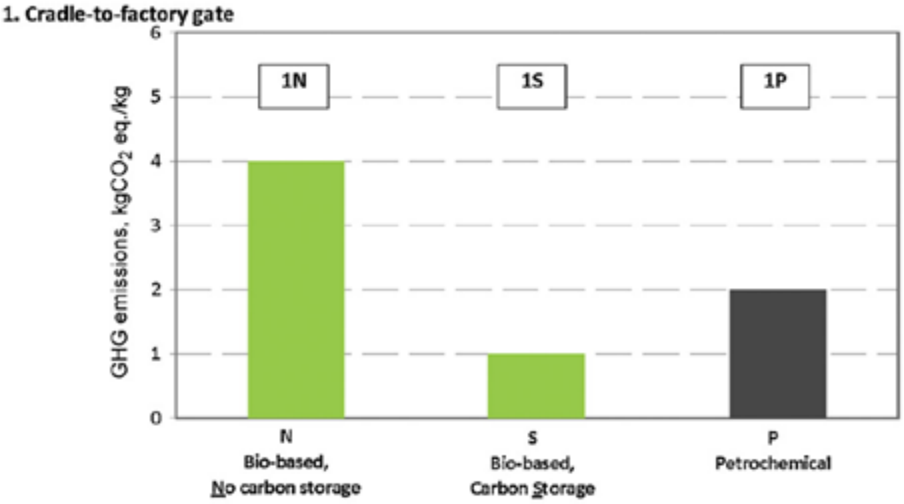


Figure 1. Comparison of greenhouse gas emissions for a fully bio-based material, with and without carbon storage, and the traditional fossil fuel material for a cradle-to-gate system. Data source: Pawelzik, et. al, 2013.

The overall trend is for bio-based materials to account for the carbon sequestered in its material. Additionally, since production of bio-based materials will remain in small quantities in the near future, the climactic effects from bio-based material carbon storage will be small. As the production of bio-based materials increases towards quantities of millions of tons, the larger impact on carbon storage will need to be examined further.

A concern with many bio-based material LCAs is their failure to consider the impact of land use change that may result from growing the feedstock for bio-plastics. These LCAs account for the carbon benefits of bio-plastics, but not the carbon storage and sequestration eliminated by diverting land to agricultural use (Piemonte & Gironi, 2011). Converting and expanding land to bio-product production releases 9-170 times as much CO_2 than the annual CO_2 reductions achieved from replacing petroleum products with bio-based products (Piemonte & Gironi, 2011). Additionally, bioplastics are considered an environmental benefit because of the reduction in fossil fuel resources and GHG emissions. Yet, agricultural production of raw materials can lead to other environmental impacts, such as soil erosion, eutrophication, artificial fertilizer use, and habitat fragmentation (Piemonte & Gironi, 2011).

If raw material production is done thoughtfully and land is not converted to grow bio-materials, bio-based products can indeed have a positive environmental impact compared to fossil fuel-based products. If bioplastic production uses waste biomass as the raw material, or if the plant product is grown on degraded, fallow, or marginal land where no conventional crops were previously grown, then no indirect land use will occur (Piemonte & Gironi, 2011). If no indirect land use occurs, then the LCA studies showing the reduction in GHG emissions are accurate. Additionally, GHG emissions may decrease if these conditions are met, thus creating a real advantage for the use of bio-based plastics over petroleum-based plastics (Piemonte & Gironi, 2011). This is the ideal agricultural scenario for bio-based raw material production.

2.3.2.2 Bio-Based Polyethylene Terephthalate (PET)

For bio-based polyethylene terephthalate (PET), an LCA examining environmental impacts of petroleum-based PET bottles and bio-based PET bottles found that bio-based PET bottles use 22% less fossil fuel and have 21% less global warming potential compared to petroleum-based products, when including biogenic carbon storage (Chen, Pelton, & Smith, 2016). However, there are tradeoffs, as bio-based PET performed worse for ozone depletion and ecotoxicity (Chen et al., 2016).Water use in the production of bio-plastics is also significantly greater than water use for fossil fuel plastic production. An LCA conducted for Patagonia, Inc. comparing bio-based, fossil fuel-based, and recycled PET found that water use in the bio-plastic production was 5-20 times greater than fossil fuel sources (Kuczenski & Meisterling, 2016).The LCA also found that GHG intensities for bio-PET were similar to those of virgin PET at 3.459 kg CO_2e using corn ethanol as the feedstock, 1.940 kg CO_2e using cane sugar ethanol as a feedstock, and 2.856 kg CO_2e for virgin PET (Kuczenski & Meisterling, 2016).

An LCA comparing European bio-based polyethylene to fossil fuel-based polyethylene showed GHG emission reductions with and without impact from indirect and direct land use change. Without land use change, bio-based polyethylene produced GHG emissions of -0.75 kg CO_2e/kgPET, which is a 140% savings compared to fossil fuel-based polyethylene (Tsiropoulos et al., 2015); however, when land use change is included, additional GHG emissions range from 0.16-2.38kg CO_2e/kgPET, creating a total of -0.7-1.8 kg CO_2e/kgPET (Tsiropoulos et al., 2015). This shows the significance of land use in bio-based raw material production.

2.3.2.3 Bio-Based Nylon

Nylon is a thermoplastic, with its virgin form created from petrochemicals through a chemical synthesis reacting an acid with an amino (Steele, 2005). Nylon is classified by either one or two numbers: the first indicating the number of carbons in the diamine for monomers, and the second listing the number of carbons in the diacid for co-monomers.(Legatt, 2018). The two most common forms of nylon in clothing textiles are Nylon 6 and Nylon 6,6. Nylon has been used in many commercial applications since the 1940s. In 2004, the global market produced roughly 6.6 million tons of nylon annually with applications ranging from thermoplastics for carpets to car parts to fibers for clothing (Kind et al., 2014).

Nylon 6,6 is a polyamide that is formed via a polymer condensation reaction of a dicarboxylic acid and a diamine (Thiemens & Trogler, 1991). The process results in significant release of nitrous oxide, a potent GHG (Thiemens & Trogler, 1991). Additionally, the resultant carbon dioxide emissions and the power requirements for production far outpace other commonly used plastics such as polyethylene (Vink, Rábago, Glassner, & Gruber, 2003). Advances in metabolic engineering have unlocked bio-based routes to diamines suitable for nylon production (Kind et al., 2014). Resultant LCA savings in GHG emissions are estimated at 3 tonnes of CO_2e per tonne of nylon relative to conventional production routes (Weiss et al., 2012).

Commercially available bio-based nylons are most often derived from castor oil feed stocks. Production routes rely on the conversion of castor oil into sebacic acid. A life cycle assessment conducted in 2009 compared polyol production from irrigated castor farming to that of traditional petroleum feedstocks utilized by PlasticsEurope (Helling & Russell, 2009). The study found that irrigated castor oil resulted in a 102% reduction in GHG emissions relative to the petroleum derived polyol (Helling & Russell, 2009). Conversely, the water intensity increased to a value of 396% of conventional European petrochemical production (Helling & Russell, 2009). Sensitivity analysis showed these choices had massive impacts on both GHG emissions and water use. Modifying these assumptions can result in GHG emission estimates for castor-derived polyol of 13- 46% of that of PlasticsEurope petrochemical values, while water intensity values can range from 35- 840% (Helling & Russell, 2009).

2.3.2.3 Recycled Polyester

Globally, over 70% of recycled PET is converted into polyester fiber (Shen, Worrell, & Patel, 2012). Rather than using virgin PET, recycled polyester is produced using pre-consumer PET, and post-consumer PET, such as recycled bottles or worn-out garments. The production of both virgin and recycled polyester has environmental impacts, but a multitude of LCA studies demonstrate that recycled polyester has improved environmental performance over its traditional counterpart (Sandin & Peters, 2018)

According to a comprehensive review of academic literature analyzing textile reuse and recycling, LCAs of recycled textile fibers most frequently utilize the cut-off and system expansion methods to set the system boundary. Under the cut-off approach, the first life of the virgin PET and its associated environmental impacts are considered separate from its second life when it is recycled into polyester fiber (Sandin & Peters, 2018). Practically, this means that the first process included in the system boundary for recycling PET into polyester fiber (i.e. cradle) is collection of post-consumer waste (Shen, Worrell, & Patel, 2010).

The system expansion method considers the entire life cycle of producing virgin PET and recycled polyester fiber as separate systems. As a result, the processes to produce virgin PET are included in the system boundary of producing recycled polyester. This means that the environmental impacts of virgin PET production are double counted between both systems (Shen et al., 2012).

Another allocation method less often used in LCAs of recycled fibers is the waste valuation or avoided burden approach. Under this method, the environmental burden of virgin PET production is shared between its first life as PET and second life as recycled polyester fiber (Shen et al., 2012). As a result, LCAs of virgin PET production include some of the environmental benefits of recycling. GHG intensities derived from LCAs of recycled polyester fiber using the waste valuation method are thus higher than those from LCAs using the cut-off approach because some of the environmental benefits are shared with virgin PET production (Shen et al., 2010).

Another critical and widespread assumption within the academic literature is that production of recycled polyester completely replaces the production of virgin polyester. Most studies assume a 1:1 replacement rate, but this is not always the case for all garments. Notably, it has been shown that the environmental benefits of recycled polyester can be diminished when replacement rates are low (Sandin & Peters, 2018). This indicates that in some cases, replacing virgin polyester with certain proportions of recycled polyester increases the overall environmental impact of the product. Further research is needed to determine how replacement rates affect the environmental impacts of different material and product applications (Sandin & Peters, 2018).

One of the primary limitations of recycled polyester LCA studies is that the narrow focus on the climate change impact category may cause other environmental benefits and costs of the material to be overlooked. Recycled polyester could offer improvements in the land use impact category as compared to virgin bio-based materials (Sandin & Peters, 2018). Further analysis of other impact categories is fundamental for consideration of the full range of environmental benefits and costs from recycled polyester.

Production of polyester using post-consumer recycled bottles can be achieved through two avenues: mechanical and chemical recycling. Mechanical recycling transforms PET flakes, pellets, or chips into polyester through melt-extrusion (Shen et al., 2010). This process is also sometimes referred to as thermal recycling and is not to be confused with thermal recovery, which produces electricity through incineration of textile waste (Sandin & Peters, 2018). In contrast, chemical recycling involves breaking down the PET polymers into monomers or oligomers to produce recycled polyester. Generally, mechanical recycling has a lesser environmental impact compared to chemical recycling, but chemical recycling yields a higher quality polyester that is nearly identical to virgin polyester (Shen et al., 2010).

Across cradle-to-factory gate LCAs, recycled polyester is found to have significantly improved environmental performance compared to virgin polyester. The seminal study by Shen et al. (2010), which is the data source for mechanical recycling in the Higg MSI, found that the global warming potential (GWP) of mechanically recycled PET fiber is 0.96 tons of CO_2e per ton of fiber as compared to 4.06 tons of CO_2e per ton of virgin PET fiber. This translates to a 76% reduction in GWP when using recycled polyester (Shen et al., 2010). Energy used throughout the production process is the primary driver of the overall environmental impact. According to Shen et al. (2010), freshwater aquatic ecotoxicity is the only category in which recycled polyester had a higher impact than virgin polyester. While the impact of recycled polyester is nearly 5 times higher in this category, it can be primarily attributed to small aqueous emissions of vanadium (Shen et al., 2010).

In a cradle-to-gate life cycle assessment of virgin and secondary (recycled) PET bottles in the state of California, recycled PET bottles were found to have significantly higher eutrophication impacts as compared to virgin PET bottles (Kuczenski & Geyer, 2011). Producing recycled PET bottles requires similar collection and processing necessary to produce recycled PET fiber, therefore the results from this study are worth considering in an apparel context. Higher eutrophication values for recycled PET are largely driven by post-consumer reclamation of virgin PET. During the reclamation process, post-consumer PET is washed and the disposal of this wastewater with organic materials significantly drives the higher eutrophication impact. Across the entire life cycle of PET bottles, reclamation alone accounts for 10% of total eutrophication impacts (Kuczenski & Geyer, 2011).

When comparing the environmental impacts of mechanically recycled PET to natural fibers, rather than other synthetic fibers, it is not always clear which has the lower impact. According to a review of recycled fibers by Sandin & Peters (2018), the allocation method used in the LCA can affect the conclusion. For instance, recycled PET analyzed using the cut-off method has a lower GWP than virgin tencel. In contrast, the GWP of recycled polyester under the waste valuation method is higher than that of virgin tencel (Shen et al., 2012). Overall, the different allocation methods and system boundaries used in LCAs of recycled PET result in a potential range of GWP savings between 25-75% as compared to virgin PET (Shen et al., 2010). Comparisons of this nature between fabric types are of course only valuable when the materials are interchangeable for a given product, which is not always the case.

Production of recycled PET from worn-out garments involves a specific type of chemical recycling called methanolysis. In this process, the PET polymers from garments are broken down using methanol to produce dimethyl terephthalate (DMT). After the DMT is extracted from the solution, it is repolymerized to produce PET fiber (Shen et al., 2010). Based on the cradle-to-gate LCA published by Patagonia (Patagonia Inc, 2005), recycled PET produced through methanolysis of old Capeline garments produced 0.98 CO_2e (metric tons CO_2/metric ton DMT), which represents a 71% decrease in carbon emissions as compared to virgin PET. Using its past garments as a source of PET enables Patagonia to address the end of life of a garment, which is typically excluded from LCAs of recycled materials. While the inventory data from this study is still used to inform more recent LCAs of methanolysis, updated primary data is necessary to gain a more comprehensive and reliable understanding of the true impacts of the process (Sandin & Peters, 2018). Ultimately, GHG intensity values for chemically and mechanically recycled PET are moving targets that are updated over time as more data is collected and new studies are conducted.

2.3.2.4 Recycled Nylon

Of the textile materials discussed in this literature review, and in general, nylon is widely considered to be the most difficult material to recycle. The creation and use of virgin nylon for use in textiles has environmental impact due to generation of GHG emissions and water usage leading to water scarcity. Two studies examining the impact of virgin nylon creation yielded similar results regarding environmental impact from GHG emissions. The first study, looking at both Nylon 6 and Nylon 6,6, was conducted using life cycle analysis software, Simapro 7.2, with GHG impact indicator in IPCC GWP 100a in kg CO_2e (Muthu, Li, Hu, & Mok, 2012). The authors concluded that the production of 1 kg of Nylon 6 virgin fiber would result in 9.2 kg CO_2e, while the production of 1 kg of Nylon 6,6 virgin fiber would result in 8 kg CO_2e (Muthu et al., 2012).

Muthu et al. did not outline whether the analysis includes just raw material production and processing, or also extrusion into filaments and drawing (also called melt spinning). A second report by the European Commission draws a clear system boundary and excluded the extrusion phase. This study concluded that 1 kg of Nylon 6 raw material production and processing creates between 10-13 kg CO_2e, using ecoinvent 2.0 database (Beton et al., 2011).

The European Commission's report did not consider water scarcity. However, it did factor in freshwater ecotoxicity, using dichlorobenzene equivalents per kg (DB eq/kg) as the impact indicator, and general resource availability using a monetary impact indicator, in United States dollars (Beton et al., 2011). Alternatively, Muthu, et al. identified water use per kg of Nylon 6 fiber was 185 kg and 663 kg/kg of fiber for Nylon 6,6 (Muthu et al., 2012); making Nylon 6,6 358% more water depleting than Nylon 6.

All recovered nylon fabric must be cut and cleaned and may be recycled by one of two processes. Nylon is re-melted and spun into yarn in mechanical recycling (McCann, 2015a). Chemical recycling, on the other hand, reduces the cut and cleaned fabric to its base molecule through de-polymerization (McCann, 2015b) then chemical additives are used to re-polymerize the molecules (McCann, 2015b).

While there are some studies of nylon recycling environmental impacts, there have not been academic studies specifically using an LCA framework. For example, Muthu et al. did not analyze GHG emissions from either chemical or mechanical processing. Rather, they only calculated the amount of energy saved from recycling versus incineration. Using data from Morris and Canzoneri, recycling either Nylon 6 or Nylon 6,6 saved 4,889 kWh/ton of recycled material versus generating 611 kWh/ton of recycled material (Morris, J., Canzoneri, 1992). Muthu et al. only calculated water use for virgin material, at 185 kg/kg of fiber for Nylon 6 and 663 kg/kg of fiber for Nylon 6,6, but not for recycled nylon processing.

Synthetic fiber recycling is an area that would benefit greatly from further research. Velden et al. notes that environmental impacts varied not just by material selection, but also by the thickness of the yarn, which most studies do not take into account (van der Velden, Patel, & Vogtländer, 2014). A comprehensive LCA of recycled nylon would ideally include recovery of used nylon fabric (transportation and sorting), processing (chemical or mechanical) broken down by each step, as well as the full fiber-to-fabric process covering the fourteen different impact categories, including global warming potential and water use.

2.3.3 Dyeing and Coloration Innovations

2.3.3.1 Solution Dyeing

There are a variety of dyeing technologies and techniques, each with benefits and challenges. Dye methods are largely chosen based on fabric material, desired color, and cost. Traditionally, dyeing has been a wet process in the manufacturing phase of textile production. Due to the large demand for water, chemicals, and energy, washing, dyeing, and finishing are primary drivers of environmental concerns in the textile production process (Parisi, Fatarella, Spinelli, Pogni, & Basosi, 2015). Dye process impact and emission levels vary a great deal as they are directly related to the type of fiber, dyestuff, technique, and machinery used. New dye technologies are in development largely in response to increased demand for sustainable goods in the apparel industry, and stricter industry regulation and inspections in some countries. Here we will explore conventional bath dyeing and an alternative, solution dyeing.

Post dyeing, or bath dyeing, is a traditional method, where fibers or fabric are dyed in an aqueous media at high temperature and pressure (Gürses, Açıkyıldız, Güneş, & Gürses, 2016). This notoriously environmentally degrading technology is highly energy intensive and requires a large amount of water, bleaching, and effluent treatment for dye discharge. Large amounts of water are required for textile dyeing; one study from Natural Science estimates that an average sized mill producing 8,000 kg of fabric daily uses approximately 256,000 liters of water (Kant, 2012).

Another analysis of the textile industry's environmental impact found traditional dyeing requires between 30 to 50 liters of water per kg of fabric and 60 liters per kg of yarn, depending on the type of dye used (Toprak & Anis, 2017).

A 2016 Environmental Impact of the Global Apparel and Footwear Industries global impact study of the textile industry by Quantis and ClimateWorks Foundation quantified dyeing and finishing freshwater withdrawal of 58.4 giga cubic meters (Quantis, 2018). This was measured through analysis of life cycle inventory data from the World Apparel Life Cycle Database. A study published in *The International Journal of Life Cycle Assessment* measured water use of 0.08 cubic meters to dye 1 kg of cotton fabric and 0.104 cubic meters for 1 kg of 80% cotton/ 20% PET blend (van der Velden et al., 2014). Dyeing contributes one-fifth of the total wastewater flow from the textile industry (Parisi et al., 2015). Untreated, post dyeing effluent pollutes numerous toxic chemicals into the water supply, including heavy metal-rich dyes and fixing agents, bleaches, solvents, and detergents (Kant, 2012). Many of these chemicals, including cadmium, lead, mercury, tributyltin (TBT), pentabromodiphenyl ether (PBDE), phthalates, perfluorooctane sulphonate (PFOS), and aniline (Kant, 2012), have been banned in countries due to their toxicity. For countries with large textile printing and dyeing industries, like China, effluent is often discharged untreated to cut costs for the textile mills (Liu, Shadbegian, & Zhang, 2017).

Traditional dyeing is notoriously energy intensive, which impacts the availability and cost of limited energy supplies in textile-industry dense countries like Bangladesh, India, and China (Rupp, 2008). The aforementioned 2016 Quantis study quantified dyeing and finishing's global warming potential at 1.18 Gigatons CO_2e (Quantis, 2018). A comprehensive review of life cycle inventory data by Van der Velden, et al. determined a range of GHG intensity of 1.39- 6.08 kg CO_2e per kg cotton and 2.31- 4.14 kg CO_2e per kg synthetic material (van der Velden et al., 2014). The Higg MSI measures a conventional dyeing global warming GHG intensity of 2.0515 kg CO_2e per kg of fabric based on a life cycle inventory data analysis by Murugesh & Selvadass using IMPACT 2002+ methodology. The assessment analyzed three different dyeing methods of 100% organic cotton single jersey knit global warming potentials: 12.2, 16.9, and 6.58 kg CO_2e per kg of material (Murugesh & Selvadass, 2013).

Solution dyeing is a waterless technology that reduces environmental impacts of textile manufacturing. It holds many pseudonyms: mass coloration, dope dyeing, spin dyeing, and fiber dope. In this one-step process, dyes or colorant are added to the polymer during the melt stage and extruded as colored fibers. Masterbatch method is the most common technique, in which masterbatch coloring is added to polymer chips during melt spinning (Gurudatt, De, Rakshit, & Bardhan, 2015). It has been used on numerous types of fabrics, including nylon, PET/polyester (Jiang et al., 2016), silk fabric (U.S. Patent No. 9689089B2*,* 2017), and composite fiber (U.S. Patent No. US20150240389A1, 2015). Patagonia already employs this method for some of its products.

Heralded as a sustainable option, the colorant is added before spinning into yarn, thus avoiding water baths, bleaching, and toxic effluent common in standard dyeing. Also it requires less energy, as it bypasses numerous steps in traditional packaged dye yarns and shortening the fabric production process by 7 to 20 days ("U-Long High Tech Textile Co., Ltd.," n.d.). An internal study by U-Long High-Tech Textile Co. estimates that solution dyeing reduces GHG emissions by 62%, energy consumption by 64%, and water consumptions by 89% compared to traditional methods ("U-Long High Tech Textile Co., Ltd.," n.d.).

Beyond environmental benefits, there are other advantages to solution dyeing. Solution dyed fabrics and yarn are fade and ultraviolet radiation resistant, making it an excellent choice for outdoor goods. Unlike packaged dye yarns with less thorough penetration by the colorant, solution dyed yarn and fabric have complete color uniformity ("U-Long High Tech Textile Co., Ltd.," n.d.). This method also allows for multi-function combinations to be added during the dyeing process, such as the addition of flame retardants, antistatic, or antibacterial components (Gurudatt et al., 2015).

Solution dye does have its disadvantages. It requires large volumes of material, making batches for samples or small orders a challenge. Also, this process has inherent inefficiencies as it causes heavy staining of polymerization tanks. Thus, this process requires either several tanks to execute multiple jobs, or a single tank dedicated to a single color. Lastly, as of the date of this review in 2018, solution dyeing only offers a limited range of colors and shades and is not applicable to natural fibers, such as wool or cotton.

According to the Higg MSI's database, the environmental benefits of solution dye compared to conventional dye are as follows. For global warming potential (GWP) indicated by GHG intensity, solution dyeing is two orders of magnitude smaller than the conventional batch method: solution dye has 0.0677 kg CO_2e per kg of material while conventional has 2.0515 kg CO_2e per kg of material ("Sustainable Apparel Coalition - Higg MSI," n.d.). Eutrophication potential for solution dyeing is unavailable; however, its MSI score is two orders of magnitude less than conventional dyeing. Another impact area where solution dyeing is considerably less environmentally degrading is water scarcity. In this category, the water scarcity potential is one order of magnitude smaller: the solution dyeing water scarcity potential is 0.0013 m^3 and traditional dyeing is 0.0135 m^3 ("Sustainable Apparel Coalition - Higg MSI," n.d.). Batch dyeing Higg MSI environmental analysis was based on the life cycle assessment utilizing Impact 2002+ methodology of organic cotton knitted fabrics from the journal of *Textile and Apparel Technology and Management*. Solution dyeing MSI values were approximated from ecoinvent 2014.

In addition to solution dye, there are other new dye technologies which will be examined in our analysis. These technologies also provide reductions in carbon emissions compared to traditional dye processes.

2.3.4 Carbon and Water Pricing

2.3.4.1 Models Implemented in the Corporate Sector

Recently, a variety of models have been developed and implemented within the corporate sector to quantify and value environmental impacts of businesses. These models take a life cycle perspective approach to analyzing a corporation's environmental footprint. By considering the environmental impacts throughout the supply chain, companies can quantify the environmental effects beyond internal operations.

A well-known and innovative corporate model is PUMA's Environmental Profit & Loss (EP&L) Account. Originally implemented in 2011, the EP&L valuations of PUMA's environmental impacts have informed the company's 10FOR20 2016 Sustainability Goals. The EP&L methodology has since been revised, reviewed and published as an open-source methodology by Kering, PUMA's major shareholder (PUMA, 2018). Kering's EP&L methodology involves measuring the environmental impacts of the supply chain and translating those values into monetary costs to society that affect human wellbeing. In response to the EP&L valuations of environmental impacts, Kering has implemented projects focused on improving material selection in its supply chain. For example, Kering invested in research and development of closed loop recycled polyester while also expanding organic cotton sourcing (Kering, 2013).

Kering's EP&L uses a specific suite of scientific models and frameworks to measure and quantify environmental impacts. For example, in monetizing the cost of water consumption, Kering calculates disability adjusted life years (DALY's) to quantify the health impacts of reduced water availability. Additionally, a quantile regression is used to estimate the change in the prevalence of water-borne disease and resulting effects on health due to a corporation's water consumption. Lastly, resource costs are estimated based on the desalination and transportation costs incurred with depleted groundwater resources (Kering, 2013).

While Kering's methodology serves as a strong reference, there are other models to consider. For instance, Ecolab's Water Risk Monetizer tool uses best available water basin datasets and an economic framework to calculate the risk associated with a company's water use (Ecolab, 2017). In collaborating with Kering and nearly 250 global organizations, the Natural Capital Coalition developed the Natural Capital Protocol, a framework for valuing natural capital to inform business decisions (Natural Capital Coalition, 2016). To further inform the development of a methodology for internalizing the carbon and water impacts of Patagonia's materials, additional research on the diverse models and frameworks of environmental valuation is needed. Specifically, more research is required to see how existing valuation models can be adapted to monetize the environmental impacts in the Higg MSI for Patagonia's materials.

2.3.4.2 Water Pricing

Research on water pricing began with first understanding the methodology behind the Higg MSI's derivations of the environmental impacts associated with water. To do this, the water scarcity potential calculated by the method described in Pfister et al. is explained in more detail.

The methodology requires a life-cycle inventory (LCI) consisting of quantities of water used, along with the source and geographic location of the water. There is a distinction made between consumptive and degradative water use: this analysis relies strictly on consumptive water use. A regionalized inventory of water consumption is derived from the "Virtual Water" database (Hoekstra & Chapagain, 2011). The methodology further regionalizes the data to a watershed level to calculate the resultant environmental damages associated with water usage in a particular geographic location. To do so, the water stress index (WSI) is calculated as a characterization factor for the amount of water consumption in a life-cycle impact assessment.

The WSI is defined as “the portion of consumptive water use that deprives other users of freshwater” (Pfister, Koehler, & Hellweg, 2009). It is calculated from a modified water stress value that applies a variation factor, accounting for variability in precipitation in each watershed, to the initial water stress value. This value is calculated by dividing the total water usage in the LCI for a given watershed by the total hydrological water availability (Alcamo et al., 2003). This is based off the WaterGap2 model based on data from 1961-1999 (Alcamo et al., 2003). Multiplying the calculated WSI value by the consumption water, or blue water, use gives the value for water deprivation in m^3 utilized by the Higg Index. This quantity of water is sometimes referred to as Relevant for Environmental Deficiency (RED) water (Pfister, Bayer, Koehler, & Hellweg, 2011).

The water scarcity value is then translated into a point total to be combined with other environmental impact categories in the Higg MSI through normalization. This step relies on a normalization factor representative of the average water deprivation caused by textile manufacturing. The factor is defined as the quantity 10 divided by an average of water scarcity values (m^3 of water/kg of textile) for each base material in the Higg MSI weighted by its share of global material volume (“Sustainable Apparel Coalition - Higg MSI,” n.d.).

Our analysis will focus on the values described, but the methodology developed by Pfister et. al (2009) goes on to detail how the WSI can be incorporated into subsequent calculations for damage indicators, or so-called endpoint values. The methodology utilizes the three endpoint categories for environmental damage laid out in the Eco-Indicator 99 methodology: human health, ecosystem quality and resource depletion (Goedkoop M., 2000). The calculations of these damage categories rely on the watershed level assessment of consumptive and degenerative water use that were used to calculate the WSI. Once determined, the three damage scores undergo a normalization and weighting procedure consistent with the "hierarchist perspective" set forth by Goedkoop. This is then integrated as a single damage score into existing life cycle impact assessment methods (Pfister et al., 2009).

Pfister suggests that the water damage scores could be monetized through two existing methods: LIME and ReCiPE. The Life Cycle Impact Assessment Method based on Endpoint modeling (LIME) explores a conjoint analysis approach to derive a monetary value for one unit of damage based on collections—human health, biodiversity, net primary production, and social assets—of related endpoints (Itsubo, Sakagami, Washida, Kokubu, & Inaba, 2004). Otherwise known as safeguard subjects, these endpoints are collectively calculated for their annual potential damages, and are the normalization values used in life cycle impact assessment (LCIA). The monetary value is the amount of willingness to pay per avoided unit quantity of damage of each safeguard subject. It is identified through the use of a choice-based type questionnaire aimed at local respondents, the results of which are analyzed using random utility theory.

There are two problems with the LIME methodology that prevent its adoption. The first is that while it identifies a monetary value, none of its safeguard subjects reference water in any form or usage. With more research it might be possible to add water scarcity into the normalization values for social assets under resource consumption midpoints. The second, larger problem is that the methods of obtaining the local willingness to pay are unable to be obtained, given the number of international locations that Patagonia sources from.

European Union (EU) Member States are promising sources of information on water pricing methodologies since the implementation of Article 9 of the EU Water Framework Directive. This article introduced cost recovery for water services, in which the environmental and resources costs of water use are internalized into the price of water. While the goals of the legislation are clear, the methods of implementation in each member state are highly heterogeneous, with each country internalizing different environmental effects of water use (European Environment Agency, 2013). Further research into specific Member State methodologies is needed to determine if there are relevant models that can be used to monetize the Higg MSI values.

In a study for the EU analyzing government interventions of the energy market, DG Energy estimated the monetary values of a variety of environmental externalities not included in European Member State energy prices. To do this, DG Energy used the EU's External-E Tool, which uses LCIA data and different monetization methodologies to estimate monetary values for 18 environmental impact categories. As a whole, this method takes a damage cost approach, accounting for all societal costs over a long-term timescale (Alberici et al., 2014b). Under the ReCiPe LCA framework, specialized methodologies are used to convert LCIA midpoints to endpoints for each environmental impact. For water depletion, DG Energy used Kering's methodology from the EP&L Account to convert water scarcity to willingness to pay for water benefits. This method yielded a price for water of €0.20/m^3 (Alberici et al., 2014a).

While not a monetary valuation methodology, the Available WAter REmaining (AWARE) water footprint method may be useful when thinking through alternative approaches. The AWARE water footprint method was developed by Water Use in LCA (WULCA). While it draws on a similar methodology and some of the same data that Pfister does, like the WaterGap2 global model, the primary difference is that AWARE accounts for the water available after deducting current demand.

According to Bakker (2014), economic valuation of water has been highly advocated by proponents of market environmentalism, with the idea that setting a monetary price on environmental externalities can influence behavior. However, it is rare to find examples of water pricing models in practice due to the technical difficulty of setting prices and political controversy associated with undermining the current water utility systems. Contingent valuation is cited as one of the common techniques in theory for valuing water, but further research will be needed to identify an applicable model of environmental valuation (Bakker, 2014).

2.3.4.3 Carbon Pricing

Significant research has been conducted analyzing the impact and effectiveness of carbon pricing, or the concept of applying a monetary cost to carbon emissions. In recent years, corporations have increasingly begun to consider the cost of carbon emissions from their business practices and internalize those costs. By internalizing the cost of carbon, corporations are essentially paying the "true cost" of the environmental impacts associated with their activities. By internalizing externalities, the intention is that the additional cost to companies will influence financial and budgeting decisions to support innovative technologies and reduce emissions (Fahimnia, Sarkis, Dehghanian, Banihashemi, & Rahman, 2013).

The Higg MSI utilizes a GHG intensity measured in kg of CO_2 equivalence per kilogram of material, which follows the methodology in the IPCC Fifth Assessment Report. The concept of GWP is employed. GWP is defined as “the time-integrated radiative forcing due to a pulse emission of a given component, relative to a pulse emission of an equal mass of CO_2 (IPCC, 2014).” It has become the default metric for transferring emissions of different gases to a common scale of CO_2 equivalence (IPCC, 2014). The GWP for each GHG has been defined on a 100-year time scale and conversion factors have been calculated to translate each gas emission into units of CO_2 equivalence. The total GWP for each gas emitted can therefore be found by multiplying the conversion factor by the kg of that particular gas emitted, as calculated in the LCI stage of the assessment. The GWP potential of a given process is then the sum of the individual GWP contributions of each gas emitted.

In 2016, over 1,200 companies reported to CDP that they are currently using an internal carbon price, or intend to implement one within the next two years (The World Bank, 2016). Corporations use a wide range of prices to internalize the costs of carbon, with prices ranging anywhere from US$0.30/tonne CO_2, to US$893/tonne CO_2 (The World Bank, 2016). For many companies, the internal carbon price closely aligns with the home country's carbon price. For example, a Canadian company's price of US$11/tonne CO_2, is similar to Alberta's price level of US$15/tonne CO_2 and Québec's cap-and-trade program at US$13/tonne CO_2 (The World Bank, 2016). The company Novartis uses a carbon price of $100, in alignment with the World Bank's estimation of the social cost of carbon (Cushing & Bartlett, 2017). About half of the companies that reported to the CDP use internal carbon prices that are higher than the mandatory prices of the jurisdictions where they are headquartered (The World Bank, 2016).

With an internal carbon tax, the company charges itself a fee for its carbon emissions (Gajjar, 2018). These funds contribute to an internal fund that can be used to finance emission reduction projects that have longer payback periods (Gajjar, 2018). The price per unit of GHG emissions should be at a level that will drive the company to reduce its carbon emissions (Cushing & Bartlett, 2017). A corporation can adopt carbon pricing to be used in two different ways. Carbon pricing can be used either for carbon offsets and to provide a market value, or it can be used to internalize the cost of damages resulting from GHG emissions. The first carbon pricing mechanism identifies emission reductions associated with a project or activity, which can then be sold either domestically or internationally. Patagonia is interested in the second pricing mechanism, since the company is interested in reducing environmental impacts associated with its activities, not to sell offsets on the market. Additionally, adopting an internal carbon price can help guide decision-making at Patagonia to drive choices that will reduce climate change impacts in its supply chain (The World Bank, 2019).

Another form of internal carbon pricing is referred to as a shadow price, which is a theoretical monetary price. Unlike an internal carbon fee, where the price for a tonne of carbon emissions is used to fund emission reduction efforts, the shadow price is used for long-term planning and investment strategies for the business ("Internal Carbon Pricing | Center for Climate and Energy Solutions," 2019). The shadow price helps the company prepare for future regulation and prioritize low-carbon investments. While the price for shadow prices is also broad, many companies use a shadow price of $10 per tonne ("Internal Carbon Pricing | Center for Climate and Energy Solutions," 2019).

Recent research has examined what makes a carbon price effective at influencing behavior change and reducing carbon emissions. These studies aim to identify a carbon price that will lead to a significant reduction in carbon emissions without being priced too high or too low. An Australian study found that pricing carbon at $23 per tonne was too low to change behavior (Fahimnia, Reisi, Paksoy, & Özceylan, 2013). More significant change was seen at a carbon price of $46, so much so that a doubling in carbon price led to four times the reduction in carbon emissions (Fahimnia, Reisi, et al., 2013).

3.0 Methods- Research Question 1

3.1 Identifying Greenhouse Gas Intensities for New Technologies

The team conducted a systematic and rigorous literature review to identify the GHG intensities (kg CO_2e/kg material) for alternative raw material and dye technologies. These values, derived from life cycle impact assessment, measure the radiative forcing of greenhouse gases using the GWP 100 indicator. It is important to note that GHG intensity values do not inform the resulting damage from the environmental impact, which would include the modeled harm to human health, ecosystem quality, or loss of natural resources.

GHG intensity values for conventional technologies were found in the Higg MSI or provided by Patagonia. To identify alternative technology GHG intensity values, a combination of Higg MSI data, supplier data, and scientific literature were referenced. Higg MSI and Patagonia data were the primary sources, and if values were not available there, other sources were consulted.

As was previously mentioned, the Higg MSI is a cradle-to-gate material scoring tool and database that provides information on the environmental impacts of the five stages of textile production: raw material source, yarn formation, textile formation through knitting or weaving, textile preparation, and dyeing and coloration (Sustainable Apparel Coalition, 2016).

In the Higg MSI, the GHG intensities associated with each process of the garment creation process are identified as “midpoints.” The definition used by the Higg MSI for “midpoint” is not the same as the definition for “midpoint” in the LCA community. The focus of this project is on climate change midpoints, or the GHG intensities given as the rate of GHG emissions per unit of material. Climate change is measured in kilogram of carbon dioxide (CO_2) equivalence as calculated by the IPCC global warming potential method.

Higg MSI uses data from a variety of sources, including academic papers and LCI databases, such as GaBi and ecoinvent. To examine the quality of the data in the Higg MSI, the team evaluated the values referenced by the Higg MSI by comparing the cited value in Higg with its data source in either GaBi or ecoinvent. This revealed that GHG intensity values in GaBi and ecoinvent databases did not align with Higg MSI values. This discrepancy exists because the Higg MSI data may be referencing a previous version of the database, which used older data. New research in the LCA field is continuously conducted and technological innovations occur in the material process making the processes more efficient. We believe this is why the GHG intensities are slightly lower in the LCI databases than the values given in the Higg MSI.

If GHG intensity values were not available in the Higg MSI, values were identified in the scientific literature. Cited sources provided either direct GHG intensity values or percent reductions from conventional materials or dye processes. If a percent reduction was given, the reduction was applied to the GHG intensity given for the conventional technology in the Higg MSI. Lastly, some of the material technologies were so new that no academic research was available. In these cases, supplier data was used to identify the GHG intensities. However, data quality was often not as robust as the previous data sources. Some suppliers conducted internal LCAs, but many of the suppliers shared only percent reductions and failed to cite sources.

3.1.1 Allocation Methods

Since many of the product changes under analysis in this project evaluate the environmental benefit of recycled raw materials compared to virgin raw materials, particularly the use of recycled synthetic materials, the team needed to establish an allocation methodology it would follow. In life cycle assessment, the chosen allocation method greatly impacts the amount of GHG savings a certain technology can claim. This analysis used the recycled content method.

As informed through the literature review, cut-off method, or recycled content method, was used to establish boundaries for recycled raw material sources. The cut-off principle considers the life of the first product, from virgin material, and that of the second, from the recovered material, as separate systems. Polyethylene terephthalate (PET) will be used here as an example. In practice, this means to calculate the cradle-to-gate GHG intensity of virgin plastic, all of the GHG emissions from fossil fuel production to finished plastic need to be added together. Cradle-to-gate emissions of recycled plastic starts where the plastic waste is generated, and the first GHG emission counted is at the collection of plastic waste. There is no GHG burden associated with the recovered plastic scrap.

In recycling, other sectors commonly use the waste valuation method, otherwise known as the avoided burden approach. The waste valuation method expands the product life cycle to include the collection and recycling process in the original product's life cycle. This addresses the criticism that the cut-off method fails to consider the benefit of recycling, as it considers the initial discard as the product's end of life. The expansion of the product life cycle causes an increase in GHG emissions. However, this is offset by subtracting GHG emissions of virgin material production, which is assumed to be avoided by the additional functions.

The 2018 comprehensive review of academic literature by Sandin & Peters, analyzing textile reuse and recycling, showed that most textile LCAs utilized the cut-off or system expansion approaches. In addition to aligning our analysis with sector practices, the cut-off method was used for two reasons. First, only 9% of plastics generated between 1950-2015 are actually recycled (Geyer, Jambeck, & Law, 2017). Although it is not clear what will happen at the end of life for those plastic products, it is not likely to become recycled feedstock for new products. Second, the avoided credit from using the waste valuation method may go to a company that makes products from virgin materials that may not be recovered, recycled, and sold as a recycled product. Ultimately, it is unknown whether it would in fact displace any virgin raw material production.

There are two methods for recycling synthetic materials: chemical and mechanical. Patagonia currently uses recycled PET and recycled nylon in its products. For recycled PET, the GHG intensity is an average of mechanically and chemically recycled PET, 1.716 kg CO_2e per kg of material. Patagonia uses an average because its product management system, the Product Line Management (PLM), cannot always distinguish between chemical and mechanical recycling.

Additionally, Patagonia uses minimal chemically recycled PET. For recycled nylon, the process is mechanical and the GHG intensity is 1.339 kg CO_2e per kg of material.

Most LCAs of bio-based plastics include biogenic carbon, which means the bio-based plastic is given credit for sequestering carbon, but few consider the impact of land use change that results from growing the feedstock. The LCA referenced in this project for bio-based PET, Kuczenski (2016), includes land use change in its analysis, while the thinkstep (2016) LCA for bio-based nylon does not. Data sources for bio-based PU and TPU failed to indicate whether they included biogenic carbon or land use changes.

3.1.2 Data Quality Ranking

A data quality ranking system was created to identify the quality of data sources (Figure 4). The ranking was created to measure data quality and assurance. Noting differences in data quality was imperative because supplier reports often had unclear references or methodology. This quality ranking was also referenced when crafting our final recommendation to Patagonia for which product changes to pursue. Each data source cited for new GHG intensity values was ranked from 1-3: a ranking of 3 was low quality data, with unclear references, or unclear methodology; a ranking of 2 was medium data quality, with some limited references or methodology; and a ranking of 1 was high data quality with sound references and methodology.

3.1.3 Assumptions

A number of supplier reports presented GHG emission changes in the form of percent reductions. It is assumed that these reductions are measured relative to the GHG intensities of the traditional counterparts for each material or dye process. For example, GHG reductions from a bio-based lining are relative to the GHG intensity for the raw material of the synthetic lining. Based on this assumption, new GHG intensities for these technologies are calculated by applying the percent reductions to the GHG intensities for the traditional counterparts from the Higg MSI.

4.0 Methods- Research Question 2

Before data analysis and calculations, the team organized Patagonia’s large dataset to only include data necessary for calculations.

Using product data from Patagonia in conjunction with Patagonia's Carbon Footprint Report, the team confirmed material production GHG emissions for 2017 were accurate at 121,588 tonnes CO_2e—only a 0.05% difference from those reported in the Carbon Footprint Report.

After Patagonia identified opportunities where material and dye substitutions existed in their product portfolio, the team developed 61 potential product changes. These changes, referred to as product swaps, change the GHG intensity values for the existing material or dye processes with the GHG intensities for the new technologies identified in the literature review. The product swaps fall into three temporal categories: near term (2019-2024), mid-term (2025-2029), and long term (2030-2034). These temporal categories are based on Patagonia's upcoming product changes and the technical feasibility of the materials and dyes.

4.1 Product Swap Index (PSI) Criteria

To keep track of the 61 product changes, the team developed a naming protocol called the Product Swap Index, or PSI. Four product change scenarios were considered in this analysis, as listed in Table 2.

Table 2. Breakdown of scenarios organizing the product swaps under analysis.

Scenario	**Description**	**Timeframe**
1	All near term & 2 mid-term solutions	2020-2024; 2025
2	Large Category Shifts	2025-2029; 2030-2035
3	Bio-Based Switch	2025-2029; 2030-2035
4	Dye Technology Switch	2025-2029; 2030-2035

In order to easily identify which product swaps are affected by the different scenarios, a numeric indexing scheme was created. Product swap indices for scenario 1 include specific years of implementation (Table 3) while product swaps in scenarios 2-4 include the general timeframe (Table 4).

Table 3. Numbering scheme for products swaps in scenario 1.

Index Numbering Scheme for Scenario 1 Scenario.Timeframe.Year.ProductSwap			
Scenario	Timeframe	Year	Product Swap*
1	Near Term= 1 Mid Term= 2 Long Term= 3	2020 = 1 2021 = 2 2022 = 3 2023 = 4 2024 = 5	Year 1 = 1-12 options Year 2 = 1-8 options Year 3 = 1-3 options Year 4 = 1-2 options Year 5 = 1-6 options

For example, PSI 1.1.5.4 would be interpreted as Scenario 1, Near Term, Year 5, Product Swap #4.

Table 4. Numbering scheme for products swaps in scenarios 2-4.

Index Numbering Scheme for Scenarios 2-4 Scenario.Timeline.ProductSwap		
Scenario	Timeframe	Product Swap*
2 3 4	Mid Term= 2 Long Term= 3	Mid = 1-10 options Long = 1-5 options

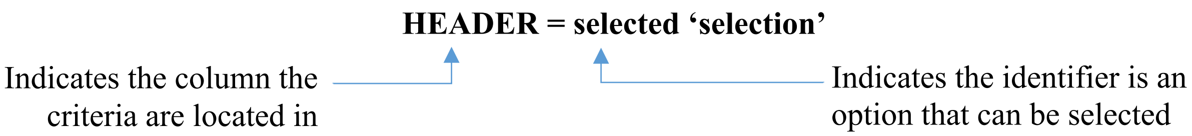
**The Product Swap index number is arbitrarily matched to a Product Swap.*

For example, PSI 3.2.9 is interpreted as Scenario 3, Mid Term, Product Swap #9.

4.1.1 PSI Inclusion Criteria

To limit new GHG intensity calculations to their respective product substitutions, inclusion criteria for each product swap were established. Product swap inclusion criteria range from using only one level criterion to using up to 4 levels of criteria and multiple sub-criteria. Inclusion criteria are based on column headers from Patagonia's product dataset. Sub-criteria are based on the filter options available under each header. Using the Excel filter, the highest, most comprehensive product identifier or characteristic was chosen that captured all the products in a product swap. From there, the inclusion criteria narrowed, continuing to use the Excel Filter until all elements outside the scope of the product swap were excluded.

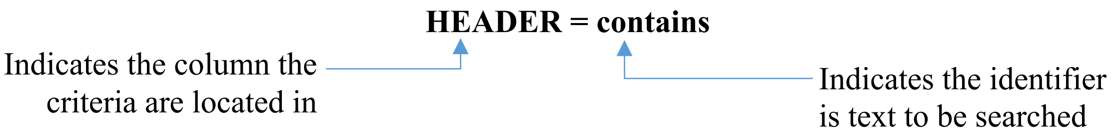
Within the Excel filter there are two features that are used to accomplish this: selection and text searches. Inclusion criteria instructions are formulated in one of two ways:



HEADER = selected 'selection'

Indicates the column the criteria are located in

Indicates the identifier is an option that can be selected



HEADER = contains

Indicates the column the criteria are located in

Indicates the identifier is text to be searched

For example,

```
PRODUCT SEASONAL NAME = contains "individual style name"
```

indicates the column header to reference is titled “Product Seasonal Name,” and that the text to search for is “Los Gatos.” Once that column header is filtered all products relevant for that product swap were identified.

Below is an example of a more complex inclusion criteria:

```
TEAM = selected 'Equipment,'
and
CATEGORY = selected 'Day Packs'
and
PRODUCT SEASONAL NAME = contains
"individual style name"
```

This Inclusion Criteria shows that three levels of criteria were needed to find the specified product swap. The first column header to reference was titled “Team” and the option to select was “Equipment.” Once this was completed, the next column header to reference was titled “Category” and the option to select was “Day Packs.” Finally, the last column header to reference was titled “Product Seasonal Name” and the text to search for was the specific style name. Once all three columns were filtered, all products relevant for that product swap were identified.

There were two outliers to this method, where filters needed to be cleared before proceeding to the subsequent filters, as there was no single product identifier or characteristic to capture all rows relating to the product swap conducted. Below is one such example:

Sorted SUPPLIIER = contains "specific supplier name"
to identify all Style Numbers
and
Cleared filter
and
Marked all rows that matched those style numbers

This type of filtering criteria was applied to all the product swap changes.

4.2 Assumptions

The methodology employed in this analysis was predicated on a variety of important assumptions. This analysis used fiscal year 2017 (May 1, 2016 – April 30, 2017) as the baseline. Two exceptions existed in our analysis looking exclusively at FY17. The project analysis also included data on the Micropuff sweater, which debuted in 2018, but was added into the FY17 dataset. As a popular item in the product portfolio, this product was asked to be included in the analysis.

Based on the desired material and dye replacements, it was assumed that the new GHG intensities sourced from the SAC's Higg MSI, supplier data, and scientific literature are representative of the Patagonia products under analysis.

This analysis assumed that replacing material or dye technologies in Patagonia's products only changed the GHG impact of the affected stage of textile production. The material and dye technologies applied in this analysis affected either process 1, raw material source, or process 5, dyeing and coloration. As such, the GHG intensities for each new raw material or dye technology were only replaced for these two stages, as applicable under each product swap. It was also assumed that changing the raw material or dye technology did not affect the emission reduction of the other three textile production stages; therefore, the GHG intensities for processes 2, 3, and 4 were kept the same across all product swaps.

Additionally, this project assumed material weights provided in Patagonia's bill of materials stayed the same when raw material sources changed in product swaps. For example, when switching from natural to synthetic materials, the team assumed the same weight of natural materials were used to produce the synthetic version. We acknowledged that this might not be the case when going from heavier fabric to lighter, or vice versa. However, incorporating weight changes was outside of the scope of the project.

This analysis also assumed replacing an existing GHG intensity with a new GHG intensity value was a one-to-one swap. Under LCA methodology, defining system boundaries is critical to quantifying environmental impact. It was not always clear from the literature or the supplier data where system boundaries were drawn, which could influence the environmental impacts examined in this project. For this analysis, it was assumed that new product processes could be swapped out for traditional ones without any issues of truncation or overcounting.

Furthermore, new materials or dyes were assumed to fully replace their existing counterparts. Assuming a 1:1 replacement rate meant that 100% of the conventional materials or dyes currently used in Patagonia's products were replaced with the emerging technologies identified in the literature review. The exceptions were the product swaps in which only a proportion of the affected product category was changed. For example, under PSI 2.2.4 50% of a large category switched to an impact-reducing dye. Therefore, 100% of the product was dyed, with only 50% using the new dye technology.

For the GHG emission reduction calculations, material waste was assumed to contribute to the overall environmental impact, even though it was not included in the final product. To incorporate this, 3% material waste was included through the textile production process. Calculating total weight of materials thus included adding an additional 3% of weight based off of the data given for finished products. Lastly, our analysis assumed 10% annual sales growth for Patagonia.

4.2.1 Product Swap- Specific Assumptions

Among the product swaps under analysis, there were cases where placement was specified. Placement conveys where in the garment the material was situated, such as in the face fabric of a backpack or the lining of a jacket. For product swap scenarios where placement of raw material changes was unspecified, every placement of the material within the product was replaced. Alternatively, in product swap scenarios where placement of the change was specified (i.e. lining of product), only GHG intensities for that placement were replaced.

For product changes where a new GHG intensity value was unknown, the original GHG intensity was used, thus indicating no change to that specific material. Hemp, tencel, and linen did not have recycled equivalents and therefore used virgin GHG intensities.

For product swaps that included switching nylon insulation to recycled nylon insulation, the recycled nylon GHG intensity from MSI was used. For product swaps that included switching PET insulation to recycled PET insulation, the recycled PET GHG intensity from MSI was used. For any product swaps that changed a percentage of a category, a stated percentage to the total weight was applied. Then GHG intensities were multiplied by the GHG intensities by the corresponding percentages.

Unless otherwise specified, in the near-term and the mid-term product swaps, solution dye was applied for only grey (FEA), white (WHI), navy (NVYB) and black (BLK) colorway alphas. We also assumed all types of synthetic materials could be solution dyed.

For product swaps impacting product membranes, when switching from virgin PU to bio-based PU, we assumed all PU in the garment changed, including any adhesives, seams, etc. Additionally, we only changed membranes made of either EPTFE (expanded polytetrafluoroethylene) or PU. Polyester membranes are combined with polyester face and backing materials, making it difficult in the current system to identify the polyester membrane. We assumed that the polyester in the membrane changed in another product swap. Lastly, the "Composite Material Percentage" column in the dataset was used to identify membranes in a product. The smallest percentage of the "Composite Material Percentage" column is the membrane. If there was no data in the "Composite Material Percentage" column, then the membrane was the smallest percentage of the "Content" column.

For product swaps where the "face fabric" was replaced, the primary assumption was that selection included the word "main" in the "Placement" column of the data extract, and excluded the outer membrane layer. Case by case exceptions were made based on the line items in the "Placement" column after filtering down by "main." For example, line items with phrases such as “Seam Tape” or “Liner” in the “Placement” column were not considered as part of the face fabric.

The following additional items are listed to give a comprehensive list of product swap assumptions:

PSI 1.1.2.4- only the face fabric changed. All PU Mold materials were assumed to remain constant, while the rest of the fabric comprising the composite material was converted to recycled material

PSI 2.2.8- “Technical Leggings” used “Tights” instead. Reasoning: serenity leggings included only spandex and cotton, while tights use nylon. We included “Centered” and “Borderless” tights.

PSI 1.1.1.10- First all PET to recycled PET, then assumed all synthetics were solution dyed.

PSI 2.2.13- Assumed 50% of virgin PET switched to recycled natural, and other 50% to recycled PET.

PSI 3.2.1- Placement in wetsuit was not defined; thus, assumed all virgin PET changed to bio-based.

PSI 1.1.4.2- “Neo navy” = “NVYB”. Recycled wool GHG intensity value was equivalent to recycled cashmere.

4.4 Analyze Product Changes

4.4.1 Identify Products

Before calculating total GHG emission reduction for the product swaps, an intermediate step was necessary to swap all relevant GHG intensities to their new values. This involved pulling data for each product change, meaning all the line items in the Excel file that fell under the PSI inclusion criteria for an individual product swap, and changing the existing GHG intensity values for each line item to the new GHG intensity values.

As products in the data extract did not hold a unique product identifier, creating a simple, automated way of pulling the data and identifying which line items needed to change GHG intensities, was challenging. Therefore, we created a binary matrix to identify if a row was included in an individual product swap. First, we populated the large data extract as a binary matrix in the "Data" tab of the Excel sheet, which included all product information and existing GHG intensities. Each PSI was given its own column. For each product swap, Patagonia's product data was sorted and filtered so that only the line items included in that product swap were visible. These values were given a 1. Everything else in that column was given a 0. This was completed for all 61 product swaps as a way of identifying which line items in the 150,000-row data file would be impacted by an individual product swap.

4.4.2 Identify Process

After the Excel sheet was populated with 1s and 0s for all product swap indices, new lookup tables were created on their respective scenario sheets to house "new" and "old" GHG intensity values. This table also specified the PSI, the impacted Production Stage (either process 1 or process 5), and meta data explaining the change that will occur.

The GHG intensity lookup table provided the logic associated with each product swap. All rows in the lookup table represented the unique entries in the affected process of the product swap. For example, PSI 1.1.1.1 was a transition from all virgin PET to recycled PET. The lookup table listed all of the materials (process 1) used in the construction of the entire product.

To generate the lookup table:

- Filtered the full data extract to include only products impacted by a given process (Filtered each PSI column to only show 1s)
- Columns to define the before and after scenario associated with the product swap were copied to a blank sheet, including the GHG intensities and the production stage.
- All duplicates were removed.
- The end result was a simple before and after that can be used to populate the "new" GHG intensities in the matrix located on the "Data" tab.

All existing GHG intensities were listed in an "old" GHG intensity column within the lookup table. Based on the nature of the product swap, new GHG intensities were manually populated in the "new" GHG intensity column. Each cell with a new GHG intensity was linked to a master table on a separate sheet. Values in the "new" column of the table represented what the GHG intensity would be for each impacted material after the product swap occurred. Many of the "new" values listed would be equivalent to the "old" values because the impact did not change. This was because products are made up of a combination of numerous component materials and only one type of material or dye was changed. Even though a new GHG intensity value was not given, it still needed to be listed in order to calculate the total impact.

4.4.3 Create an Array of New GHG Intensities

Once the affected products, process, and new GHG intensities were identified, all new GHG intensities were populated in the "Data" tab. An IF statement was used to populate the new array of GHG intensities in a second matrix in the "Data" tab. For each PSI column in this new array, the equation was only added to rows that had a "1" from the binary filter described above. This ensured that the GHG intensity value only switched for products exclusively affected by the given product swap. Conceptually, the IF statement can be expressed as follows:

IF(Process = PSI Process, LOOKUP(Affected Attribute, returns new PSI GHG Intensity)

This equation would check to see if the process listed on the "Data" tab matches the process impacted by the product swap, if so then the function would match the affected attribute to the lookup table and swapped out the "old" GHG intensity for the "new." Reference attributes depended upon the logic of the specific product swap, but were typically the "MSI Name" column for material swaps and the "Production Stage" column for dye swaps. If a process was not impacted, the calculation returned the "old" GHG intensity that was already populated in the "Data" tab and no swap was completed. Ultimately, in each column of this new array, there were new GHG intensities for affected line items, old GHG intensities for line items that were unchanged in the product swaps, and blank cells for the line items not included in the product swap.

For more complicated product swaps, such as those that only changed a specific material placement or color of a style, additional inclusion or exclusion criteria were considered when switching the GHG intensities. These PSI required additional filtering to determine which GHG intensities were changed. A second lookup table was used for these additional criteria, as well as a different IF statement that took these specifics into account. Building on the previous equation, the new equation is conceptually expressed as follows:

IF(Process = PSI Process, IF(IFNA(MATCH(Secondary Criteria, Secondary Lookup Table,
0),0)>0, LOOKUP(Affected Attribute, Original Lookup Table), return old GHG Intensity),
return old GHG Intensity)

This equation filtered the data to only include entries included in the PSI per the binary matrix. The IF(IFNA(MATCH())) portion of the equation incorporated the secondary inclusion or exclusion criteria. More specifically, if the process of the row considered matched the process impacted by the product swap, then it moved onto the nested IF(IFNA) statement. If it did not match, then the old GHG intensity was returned. The IFNA was used in conjunction with a MATCH function to lookup a secondary attribute in the second lookup table, and return an integer value for the row in which the value was contained. If the attribute was not present in the secondary lookup table, an “NA” was returned and coerced into a value of 0. This was done because under the IF statement, a swap occurred only if the value is greater than 0.

Following this element, if the secondary attribute was present in the second lookup table, then the GHG intensity swap occurred following the same logic as introduced in the previous equation. If the secondary criteria were not met, then the original midpoint value was returned. The end result was an array with new GHG intensities for affected line items that met the process and secondary lookup criteria. All other entries that were part of the product baseline, or those marked with 1s in our binary identity matrix for that product swap, had the “old” GHG intensities populated in the new array. All items not involved in the given product swap were given blank entries in the new array.

4.4.4 Calculate Percent Savings

To calculate the change in GHG emissions, baseline emissions for the existing product needed to be calculated. The baseline for the product swap was calculated using a SUMPRODUCT function that relied on the binary matrix to remove all products not impacted by each product swap. First, the mass column was multiplied by the binary column for each PSI. That product was entered into the SUMPRODUCT, along with the existing GHG emission variables given on the “Data” tab. The SUMPRODUCT gave the total carbon impact of the products involved in the product swap using existing technologies. This process is explained conceptually below:

SUMPRODUCT((Product Mass$_t$*PSI Binary Matrix),GHG Intensity)

To calculate emissions after product swaps were implemented, a second sum product function was required. The mass column was first multiplied by the binary column for each PSI. That product was entered into the SUMPRODUCT along with the newly populated GHG intensity column. This gave the total GHG impact of the products after the product swap. This equation is the same as the equation for the baseline product swap GHG emissions, except that the GHG variable changed to reflect the new GHG intensities:

SUMPRODUCT((Product Mass$_t$*Binary Matrix),*New GHG Intensity)

After calculating baseline and new emissions, change in emissions were calculated by taking the difference. The percent savings was also calculated by dividing the change by the size of the baseline carbon impact. In addition to calculating the change in impact for the entire product swap, we also isolated the GHG emissions at the process level. Our analysis examined the GHG emissions associated with the processes of raw material production and dye, so this additional step provided details about the impact of those processes. Calculating the process baseline and process new followed the same methodology as the example given above, with an additional statement that removed all processes that were not impacted by the product swap. This method provided a more granular baseline and was appropriate for finding the percent change in GHG emissions resulting from the product swap.

This percentage change relied on 2017 data exclusively and remained constant on an annual basis. The absolute amount of emissions was dependent on the product mass, which increased over time at the assumed company growth rate.

To calculate absolute savings for a given product swap, several new variables were incorporated to enable efficient calculations. GHG intensity of a given product swap (kg CO_2e per kg material) was calculated was calculated by dividing the baseline (kg CO_2e) by the total mass of impacted product (kg). The GHG intensity remained constant throughout the timeframe studied, since both the baseline and the mass of product grew at the same rate.

Product swap GHG intensities were calculated first using the current baseline emissions and again after product swap implementation, using the new baseline calculated previously. To calculate the mass of product impacted, a SUMPRODUCT function was used with the binary matrix for that product swap and the mass column. This result was divided by 5 since each product component included all 5 material production processes represented in the data.

$$GHG\ Intensity * Mass = Emissions$$

$$GHG\ Intensity = \frac{Baseline\ Emissions}{Mass\ of\ Impacted\ Products}$$

$$Product\ Mass = \frac{SUMPRODUCT(Mass, Product\ Swap\ Binary\ Matrix)}{5}$$

4.4.5 Calculating How Each PSI Changes the Overall GHG Intensity

GHG intensities of each PSI was used to calculate the GHG intensity for the entire product portfolio. Mass percentage impacted was calculated by dividing the mass of the product (kg) by the total mass of the portfolio in 2017. This was followed by the calculations for the GHG intensity before and after PSI implementation. GHG intensity of the baseline (kg CO_2e/kg material), was calculated by dividing the Baseline (kg CO_2) from 2017 by the mass of the product (kg). GHG intensity after implementation (kg CO_2e/kg material) was calculated in the same way, but instead used the New Baseline (kg CO_2) divided by mass of product (kg). The change between those two carbon intensities was calculated, and that change was multiplied by the mass percentage impacted. This yielded the change in overall intensity for each PSI.

5.0 Methods - Research Question 3

5.1 Incorporating Company Growth for Product Swap Calculations

Growth projections were incorporated into the analysis by increasing the amount of product mass in Patagonia’s entire portfolio, and for each given product swap. The underlying assumption is that all products will grow at the same rate. The mass of product impacted was projected over the 15-year period (2020-2034) using an assumed 10% growth rate. This growth rate is an illustration and is not meant to accurately reflect Patagonia’s actual growth rate. The mass represents the total amount of a material Patagonia would produce at the aforementioned growth rate for the specific products included in a given product swap.

GHG emissions from each product swap were calculated in two matrices: one for counterfactual values and one for new GHG intensity changes associated with each product swap. The counterfactual product swap GHG emissions matrix multiplied the amount of mass in each year by the baseline GHG intensity of that product swap. The result was the total annual GHG emissions. The second matrix for GHG emissions after product swap implementation used an IF statement to swap the original for the new GHG intensity, once the year of implementation was reached. Conceptually, this equation reads as follows:

IF(Year<Year of Implementation, Baseline GHG Intensity * Mass in Year,
New GHG Intensity * Mass in Year)

Using the results from the two matrices, the change or each product swap in a given year was calculated. Changes in emissions were calculated for near term (2020-2024), mid-term (2025-2029), long term (2030-2034), and overall total savings.

5.2 Incorporating Dependencies

Across the 61 product changes, there were instances of product swaps conflicting with one another. To prevent double counting of GHG emission reductions and to track how one product swap impacted a product swap further down the timeline, all product swaps were outlined to identify these conflicts. Three types of product dependencies were identified: preceding, competing, and material-dye conflict dependencies.

Preceding Dependencies - occurred when the implementation of earlier product swaps impacted the same materials changed in the product swap. To prevent double-counting GHG emissions, the reduction in GHG emissions associated with the earlier swap was subtracted from the later product swap. For example, PSI 1.1.1.1 in year 2020 involved a switch from virgin to recycled synthetic material for an individual style. Later in 2025, all synthetics in the portfolio were switched to either recycled or renewable content in PSI 1.2.1.1. Since PSI 1.2.1.1 included the synthetic material change already switched in PSI 1.1.1.1, therefore the savings from 1.1.1.1 were subtracted from the savings in 1.2.1.1. Mathematically, this was achieved by including a Dependency Adjustment column that represented the percentage of savings realized for a given product swap, assuming preceding savings were already incorporated. The factor was incorporated into the calculation determining the overall change in GHG intensity that each product swap contributed to the overall portfolio.

Competing Product Dependencies - occurred when two product changes implemented the same raw material change or dye technology in the same time period. For example, PSI 2.2.9 occurred in 2025 and changed family A to 10% bio-based face fabric. PSI 2.2.13 also occurred in 2025 and changed a specific style included in family A to a mixture of recycled natural fiber and recycled PET. As both PSIs changed the same raw material in the same year, it was not impossible for both to occur.

An example of a competing product dependency involving dye technologies was PSI 4.2.1 and 4.2.3. 4.2.1 changed all of the dye processes in a large product category to dye technology A, while 4.2.3 changed 50% of that same large product category to dye technology B. Again, both changes occurred during the same mid-term time period. In this example, two different methods of dyes were applied to the same large product category in the same time period, which obviously wouldn't be realistic.

To address competing product dependencies, the team chose which of the competing product swaps to pursue. This decision was based on the calculated GHG emissions associated with each product swap. Product swaps that produced the largest GHG savings were chosen over the competing option. There were also instances where competing dependencies had partial overlap. In other words, some of the products included in a given product swap were included in a competing product swap. For these instances, savings were calculated by subtracting the overlapping savings.

Material-Dye Conflict Dependencies - occurred when earlier product swaps increased or decreased the amount of raw material included in a later product swap involving material-specific dye technology. This dependency occurred because some dye technologies can only be applied to certain raw materials; specifically, solution dye can only be applied to synthetic materials and natural dye can only be applied to natural fibers. Therefore, if a product swap earlier in the timeline involved changing a product's raw material from a natural fiber to a synthetic fiber, this influenced the amount of material affected by a dye product swap later on. The team tracked material changes so that the correct dye technology was applied and environmental savings were accurately counted.

5.3 Calculating Emissions Savings from Proposed Scenarios

The aforementioned scenarios were analyzed, with each requiring a decision of which product swaps to implement. In the independent analyses for each scenario, dependency adjustment factors were populated for each product swap that had preceding or competing product dependencies with overlapping savings. The adjustment factors were used in the calculation to determine the change in overall intensity of the portfolio. The dependency adjustment factor was applied to the product of the change in GHG intensity and the mass fraction of the portfolio impacted. This gave the change in GHG intensity for the overall portfolio.

The analysis assumed GHG intensity of the portfolio remained constant from 2017- 2019. Beginning in 2020, an Excel formula calculated the new GHG Intensity of the entire portfolio. For each year, a SUMIF statement was used to recalculate overall GHG intensity. This was achieved by taking the value from the preceding year and subtracting the aggregated improvements in overall GHG intensity, corresponding to PSIs that were implemented that year. If the year that the product swap was implemented matched the year analyzed, then the savings in overall GHG intensity were subtracted. This calculation was completed for each year from 2020 until 2034.

Annual emissions in each scenario were calculated by multiplying the new value for GHG intensity of the overall portfolio by that year's portfolio mass. The counterfactual was the product of the same mass multiplied by GHG intensity of the portfolio at its 2019 level, which was 17.81 kgCO_2e/kg material. The change in emissions for each year was calculated by subtracting the calculated emissions from the counterfactual.

5.4 Maintaining Emissions at Current Levels

A thought experiment was performed to evaluate how Patagonia could limit emissions in year 2035 to 2019 levels. To hold emissions constant, Patagonia would need to limit its annual growth rate to an amount that could be balanced by the implementation of product swaps analyzed in this report. GHG emissions increase was governed by the following conceptual equation, where the efficiency gain was defined as the percentage improvement in the overall GHG intensity of the full product portfolio:

If (1 + Growth Rate) * (1 - Efficiency Gain) < 1; then the overall carbon footprint decreases

To calculate this empirically, a GHG intensity fraction was defined as the GHG intensity of the overall portfolio divided by that same intensity in the year 2019. The equation was rearranged to solve for growth rate:

$$\text{Growth Rate} = [(1/\text{GHG Intensity Fraction})^{(2035-2020)}]-1$$

6.0 Results

Using the product data from Patagonia in conjunction with Patagonia's Carbon Footprint Report, the team confirmed that the carbon emissions from materials for fiscal year 2017 were accurate at **121,588 tonnes CO_2e**—only a 0.05% difference from the value reported in the Carbon Footprint Report. After including the Micropuff data, the total baseline Carbon Footprint increased to 124,140 tonnes CO_2e. As reported by Patagonia, this impact was indeed about 85% of the company's total GHG emissions.

While this analysis explored potential GHG emissions savings from raw material and dye processes, process 1 and 5 respectively, the greatest source of GHG emissions across all five textile production stages actually came from process 3, the knitting and weaving involved in the formation of each product (Table 5).

Table 5. Patagonia's baseline GHG emissions broken down by textile production stage.

Production Stage	Description	GHG Emissions (tonnes CO_2e)	% Contribution
Process 1	Raw Material Source	25,845	21%
Process 2	Yarn Formation	13,991	11%
Process 3	Textile Formation	61,493	50%
Process 4	Textile Preparation	13,161	11%
Process 5	Dyeing and Coloration	9,649	8%
Total:		124,140	100%

6.1 Identifying GHG Intensities

GHG intensities of conventional and alternative material and dye technologies were compared. Figure 2 shows the distribution of material GHG intensities for different raw material sources, including virgin, recycled, organic, and bio-based.

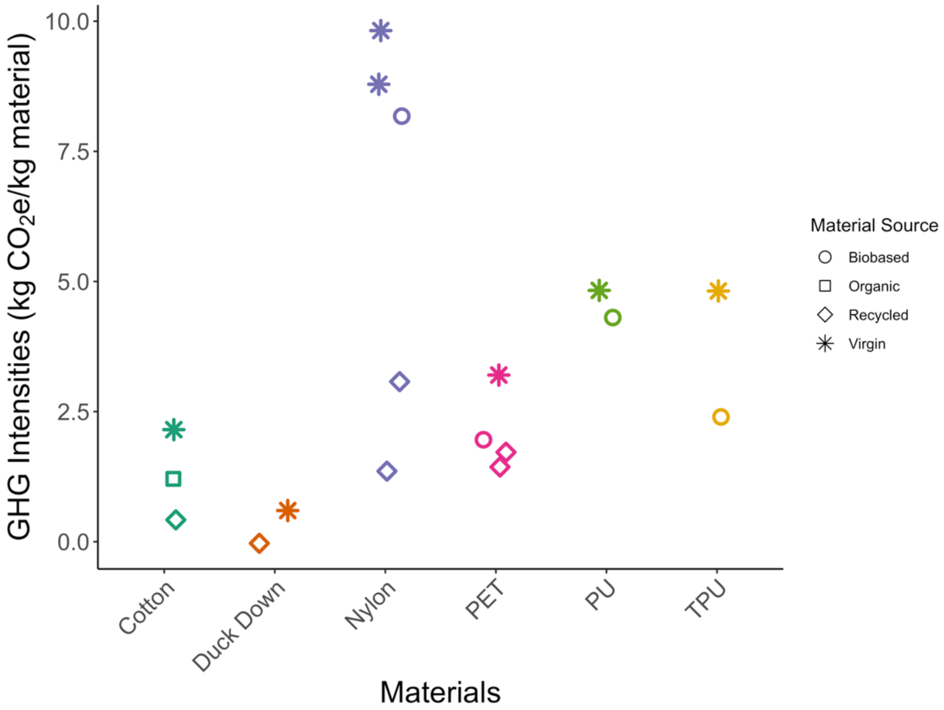


Figure 2. Greenhouse gas intensities (kg CO_2e/kg material) of production for virgin, organic, recycled, and bio-based raw material sources. PET refers to polyethylene terephthalate, PU refers to polyurethane, and TPU refers to thermoplastic polyurethane.

Unsurprisingly, virgin materials (stars) had the largest GHG intensities across all categories. For most categories, bio-based sources (circles) had the second largest GHG intensities. When available, recycled materials (diamonds) had the smallest GHG intensities. All materials benefited from switching to a recycled or bio-based source. For example, recycled nylon offered a significant reduction in GHG intensity compared to both virgin and bio-based alternatives. For polyurethane (PU), the difference in GHG intensity between bio-based and virgin was small.

In addition to raw material sources, GHG intensities for 10 methods of dyeing were compared (Figure 3). Solution dye had the lowest GHG intensity, but since this technology can only be applied to synthetic materials, its larger application throughout the product portfolio is limited. Another limitation of this technology is that currently it is only available in white, grey, navy and black colorways. However, according to Patagonia, it is assumed that after 2030 this technology will be available across the company's complete color palette. Natural dye had the largest GHG intensity and can only be used on natural materials. Due to the scope of this project, which only considers the environmental indicator of GHG emissions, this dye method would not be recommended. However, if other environmental impact categories were to be considered, a different recommendation might have resulted.

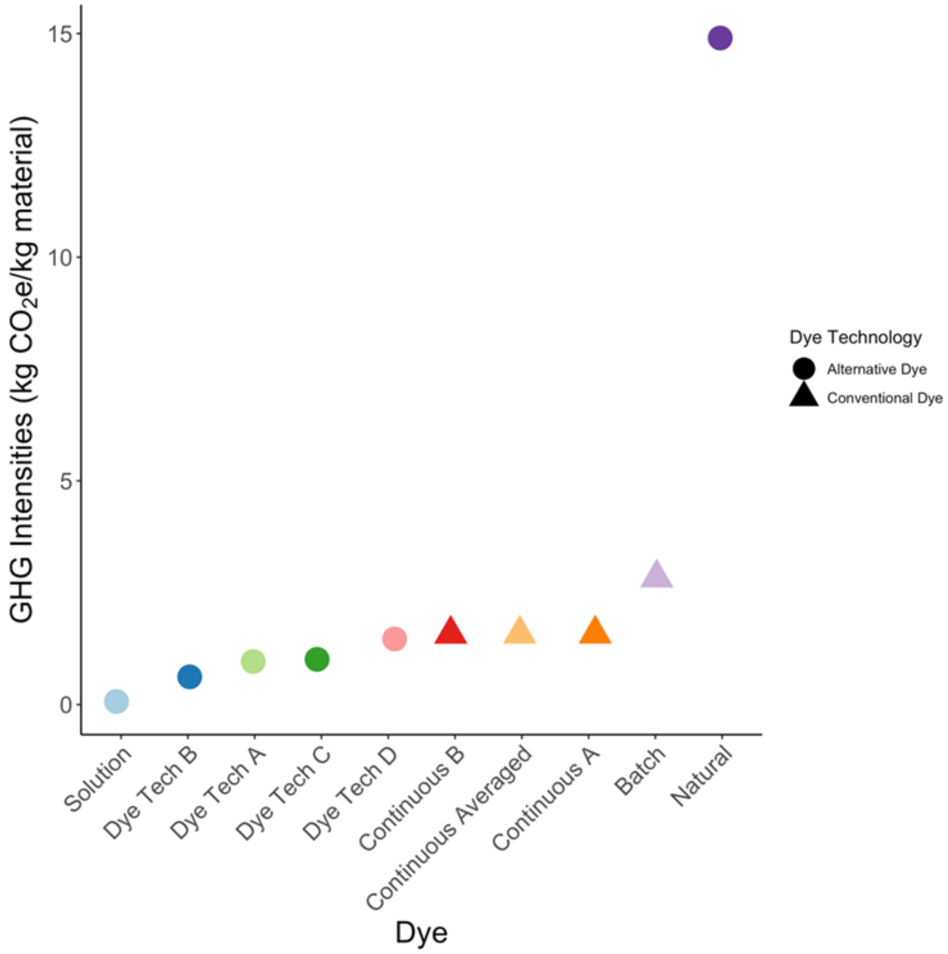


Figure 3. Greenhouse gas intensities (kg CO_2e/kg material) of production for conventional and alternative dye technologies.

When considering uncertainty associated with these values, some differences between GHG intensities within and across material and dye categories may seem small and insignificant. Yet, when these GHG intensities were applied to Patagonia's product portfolio, which consists of tens of thousands of garments sold each year, these small differences in GHG intensities led to substantial changes in overall GHG emissions. It is important to note that these GHG intensities metrics may change as new studies are conducted, which would impact potential GHG savings.

6.1.1 Data Source Quality Ranking

Sources referenced in the literature review, including scientific literature and supplier data, reported GHG intensities using different methods. Some reported percent changes compared to a conventional technology, while others reported specific GHG intensity values. Additionally, many supplier reports did not contain a clear record of their analysis or methodology. In response to this inconsistency, a data source quality ranking system was created to record details about the 21 data sources used to identify GHG intensities.

About a quarter (5) of the data sources fell in the lower rankings, due to unclear references and methodology (Figure 4). This was largely because these technologies are still in the development phase, and thus have not undergone rigorous testing or research. Moreover, many did not have LCAs conducted since they are new to the market, especially compared to conventional technologies that are more widely studied. This quality ranking informed the final recommendation for which product changes to pursue. Product swaps involving technology with unclear sources were recommended with caution, and requested that analysis be revisited when more data becomes available.

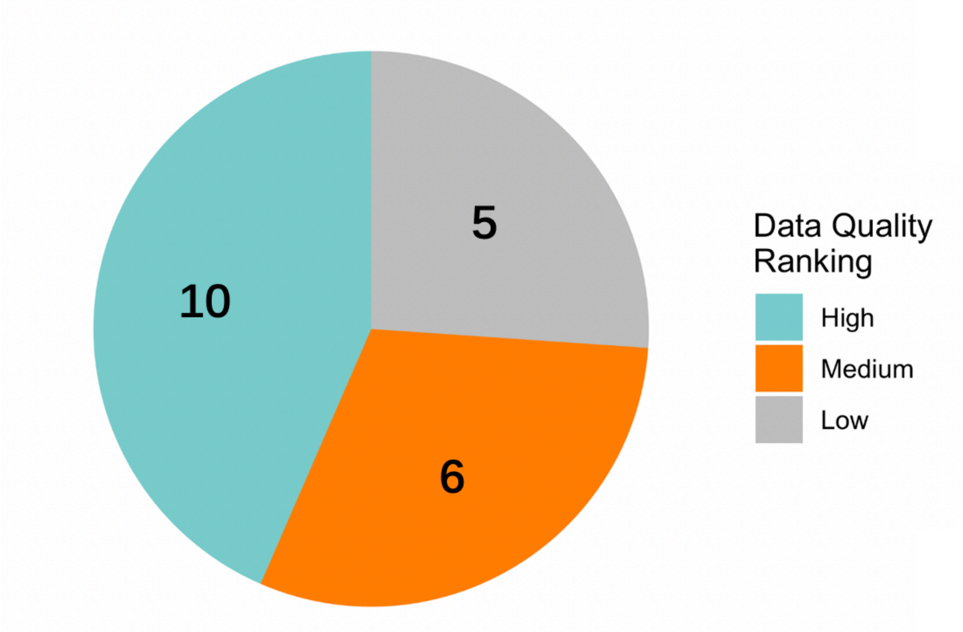


Figure 4. Data quality rankings of Life Cycle Assessment studies and supplier data. 21 data sources were cited for the greenhouse gas intensities identified for new raw material or dye technologies. Low quality data had unclear references or methodology, medium quality data had limited references or methodology, and high-quality data had sound references and methodology.

6.2 Analyze Product Changes

Product swap GHG intensities were calculated and compared to baseline levels for the year they were implemented. Change in process level GHG intensities for either process 1, raw material source, or process 5, dyeing and coloration, are shown in Figures 5a, 5b and Figure 6, respectively. Some technology swaps lowered GHG intensities, as shown by a negative slope in blue, while others increased GHG intensities and are shown by a positive slope in orange. With a few exceptions, most PSIs did not result in large changes to GHG intensities.

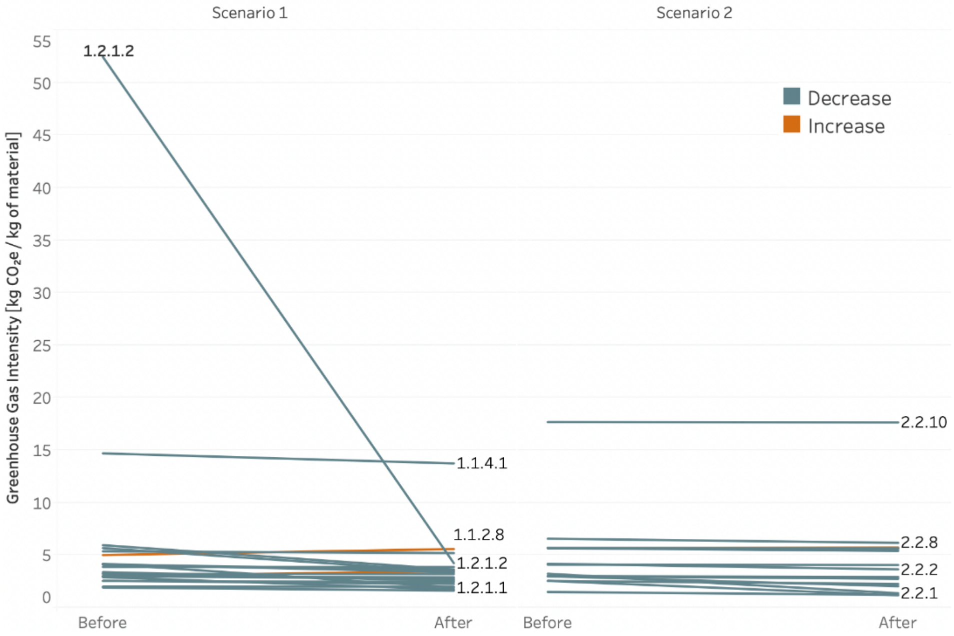


Figure 5a. Change in greenhouse gas intensities (kg CO_2e/kg material) for raw material product swaps before and after implementation in Scenarios 1 and 2. Greenhouse gas intensity increases shown in orange and decreases in blue.

Notable examples that significantly decreased GHG intensity include PSI 1.2.1.2, which changed all EPTFE material to PET by 2025 (Figure 5a), and PSI 3.2.4, which changed all EPTFE material to bio-based PET (Figure 5b). An example of a significant increase in GHG intensity was PSI 4.2.5, which switched half of a large category to natural dye (Figure 6). Out of the 61 product swaps, 55 reduced GHG intensities and 10 increased GHG intensities.

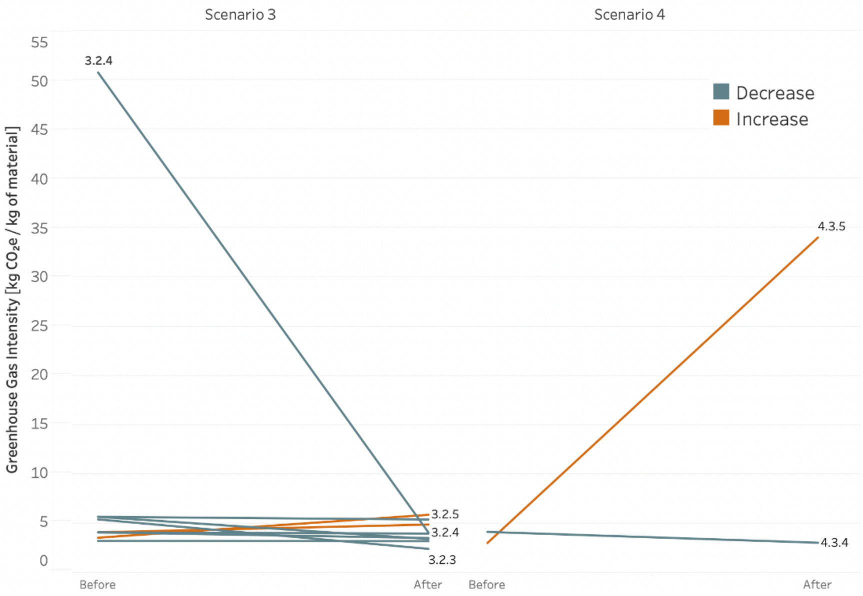


Figure 5b. Change in greenhouse gas intensities (kg CO_2e/kg material) for raw material product swaps before and after implementation in Scenarios 3 and 4. Greenhouse gas intensity increases shown in orange and decreases in blue.

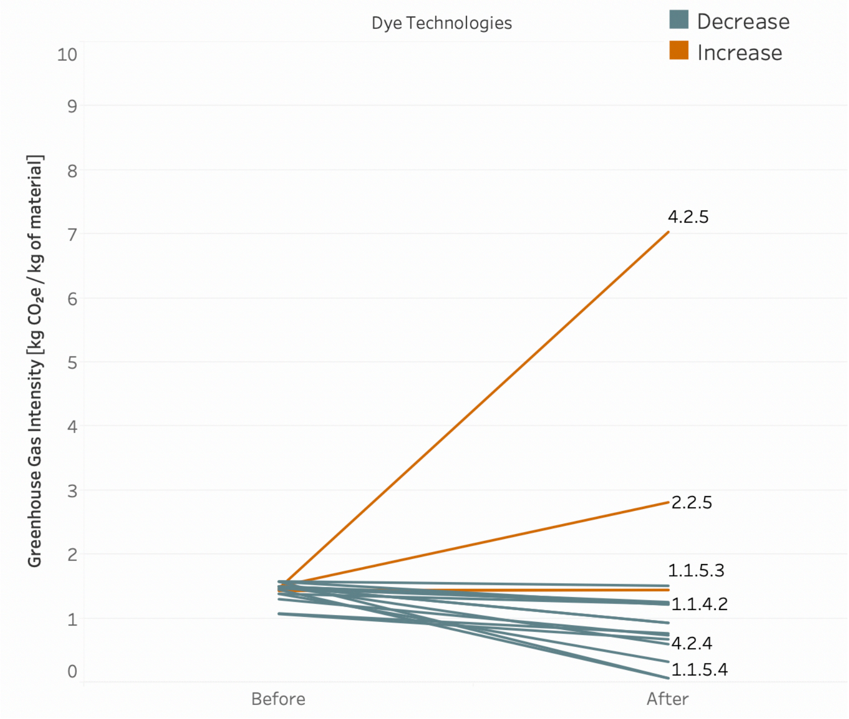


Figure 6. Change in greenhouse gas intensities (kg CO_2e/kg material) for dye process product swaps before and after implementation in all 4 scenarios. Greenhouse gas intensity increases shown in orange and decreases in blue.

Total change in GHG emissions for each PSI over the entire 15-year time period (2020-2034) is shown in Figure 7. Overall, most product changes offered GHG emission reductions compared to the existing material or dye process, illustrated by the bars beneath the x-axis. PSI 1.2.1.1 offered the greatest amount of GHG savings of about 420,000 tonnes of CO_2e, shown on the far left of Figure 7. This product swap switched all synthetic materials to the most sustainable alternative available. While this product swap caused a significant emissions reduction, implementing a product change of this magnitude is a huge undertaking for Patagonia.

As previously mentioned, some PSIs increased GHG emissions compared to the existing product materials and dyes. The largest increase in GHG emissions occurred with PSI 2.2.5, which applied natural dye to half of all products in a large category. This product swap increased GHG emissions by about 150,000 tonnes of CO_2e compared to the baseline over the 15-year timeframe, shown by the last bar above the x-axis on the right side of Figure 7. Any PSIs that increased GHG emissions compared to the baseline were not included in the final recommended strategy.

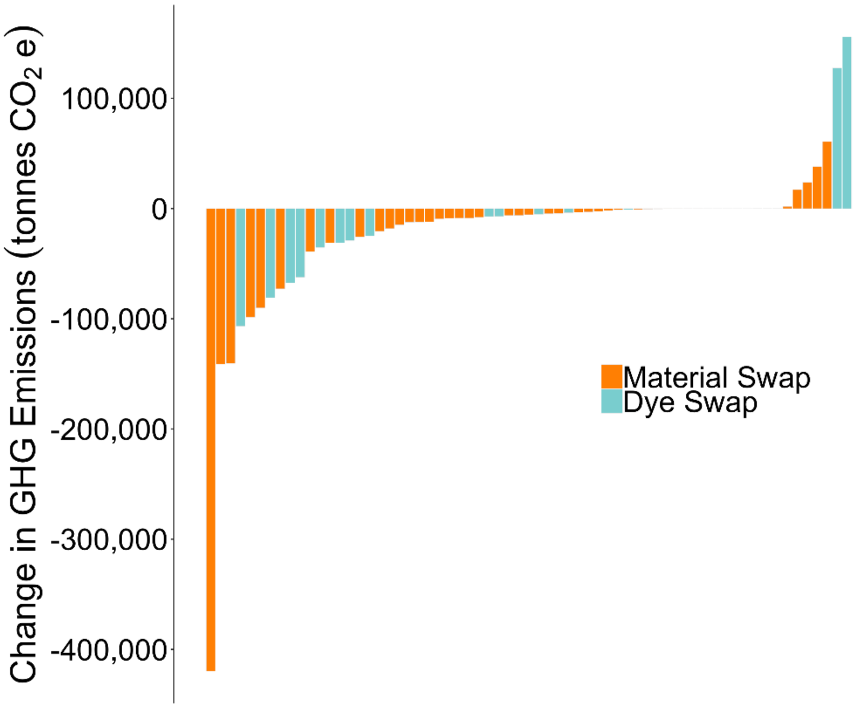


Figure 7. Total greenhouse gas emission reductions (tonnes CO_2e) for all 61 product swaps across the analyzed 15-year timeframe (2020-2035). Each bar represents a product change, or PSI. Bars that fall below the x-axis represent a reduction in GHG emissions compared to the emissions of the baseline product swap. Bars that fall above the x-axis represent an increase in greenhouse gas emissions compared to the emissions of the baseline product swap.

6.3 Analyze Growth & GHG Emissions

For the purposes of analyzing the effects of growth, the team used an assumed annual growth rate of 10%, which will increase mass of products, as well as company GHG emissions. To accurately record the emissions under the counterfactual and under each product swap, the assumed 10% growth rate was applied to the total mass of Patagonia's product portfolio. Figure 8 shows that applying an assumed 10% growth rate to the total mass of Patagonia's product portfolio is exponential.

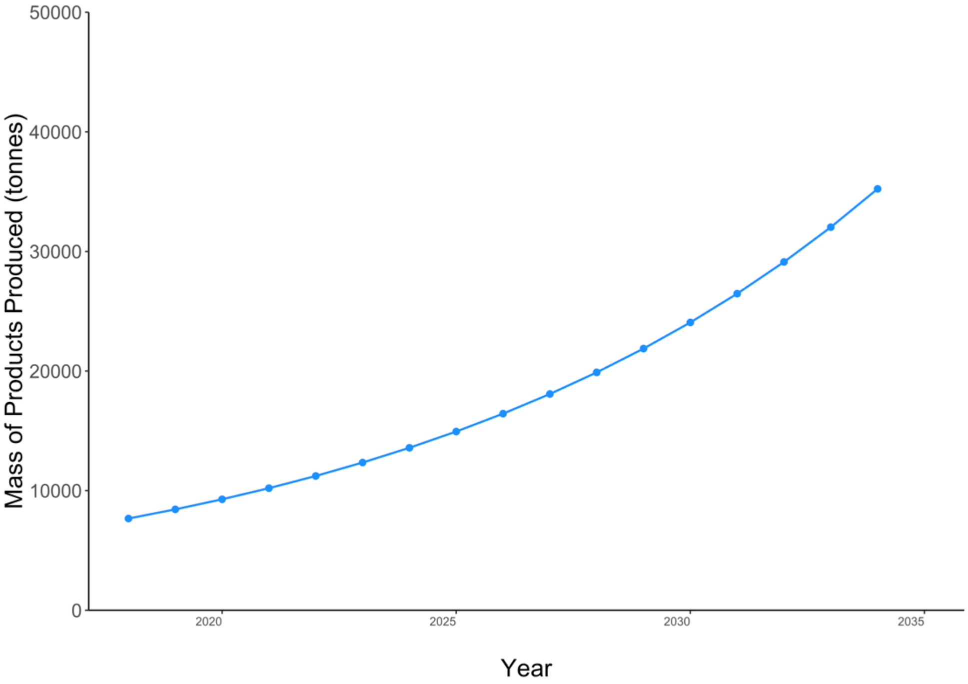


Figure 8. Mass of products (tonnes) produced annually, assuming a constant annual growth rate of 10%.

Each product swap was analyzed including the assumed annual growth. Figure 9 shows annual GHG emissions for PSI 1.1.1.1, which changed an individual style from virgin PET to recycled PET. In 2020, there was an immediate reduction in GHG emissions at the year of implementation, and the reduction in emissions compared to the counterfactual remained constant as the product mass increased until 2035. This product swap provided a 12% reduction in GHG emissions compared to the counterfactual and saved over 6,000 tonnes of CO_2e between 2020-2034. Near term product swaps, such as PSI 1.1.1.1, provided savings in the year of implementation compared to the business as usual scenario. While emissions over the period of analysis are less than the counterfactual, GHG emissions continued to grow over time as a result of assumed company growth.

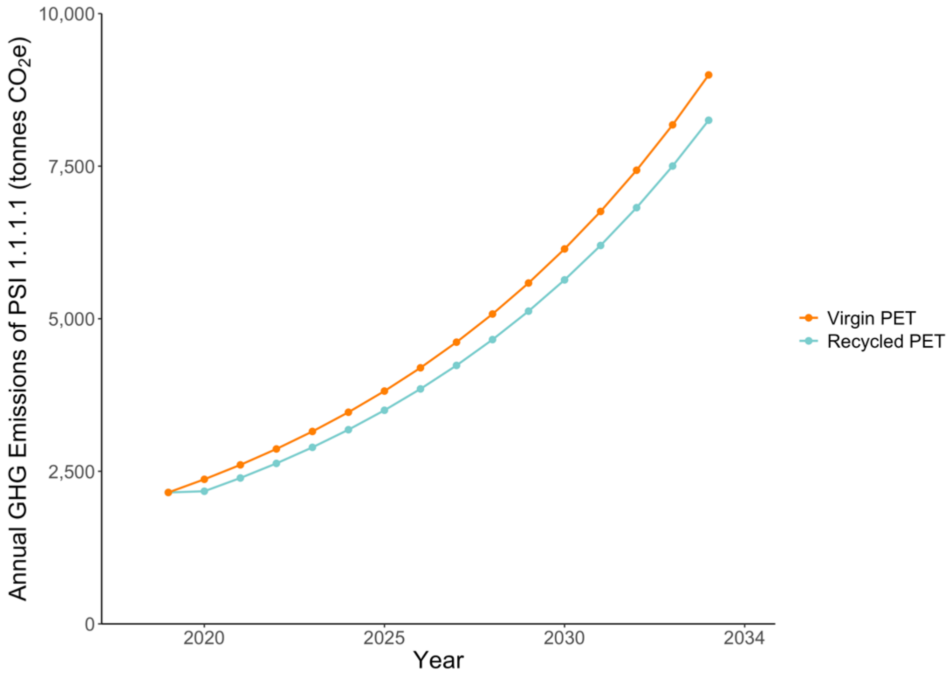


Figure 9. Greenhouse gas emissions (tonnes CO_2e) of PSI 1.1.1.1, producing an individual style with virgin polyethylene terephthalate (PET) and 100% recycled PET. Product weights increase with an assumed 10% annual growth rate.

As mentioned previously, not all product swaps resulted in GHG savings per unit. For PSI 2.2.5 (Figure 10), natural dye was applied to a large category of products, resulting in an 8.7% increase in GHG emissions compared to the counterfactual, a change of 150,000 tonnes of CO_2e. When the product swap occurred in 2025, GHG emissions immediately increased and continued to do so over the period of analysis as more products were sold. 10 out of the 61 product swaps resulted in an increase in GHG emissions and were not recommended for implementation by Patagonia.

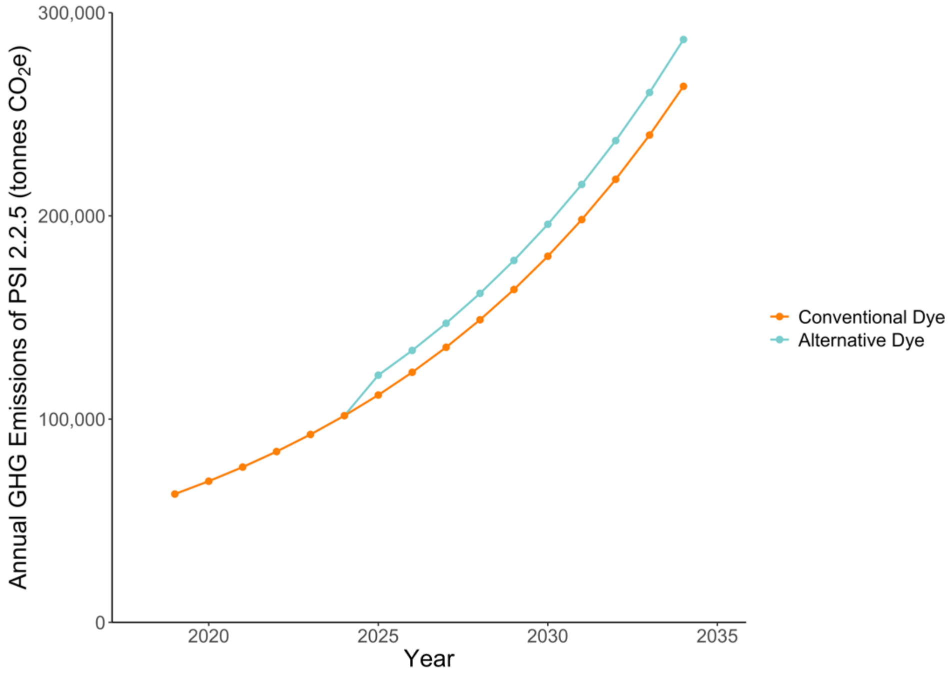


Figure 10. Greenhouse gas emissions (tonnes CO_2e) of PSI 2.2.5, switching a conventional to alternative dye for 50% of a large category. Product weights increase with an assumed 10% annual growth rate.

6.3.1 Comparing Relative Growth Rates

The rate of change of Patagonia's overall GHG emissions, or the efficiency gain, was determined by the assumed annual growth rate and the rate of reduction in GHG intensity. A tension exists between the increase in mass of products associated with assumed annual growth, and the overall reduction in GHG intensity of the products. GHG emissions would decrease if product GHG intensity decreased by implementing a product swap with an efficiency gain, and the number of units sold remained the same. However, if GHG intensity decreased and product mass increased more rapidly, or more units were sold, then company growth would counteract the efficiency gains.

Conceptually, this relationship was analyzed by the following equation:

If (1 + Growth Rate) * (1 - Efficiency Gain) < 1, then overall carbon footprint decreased.

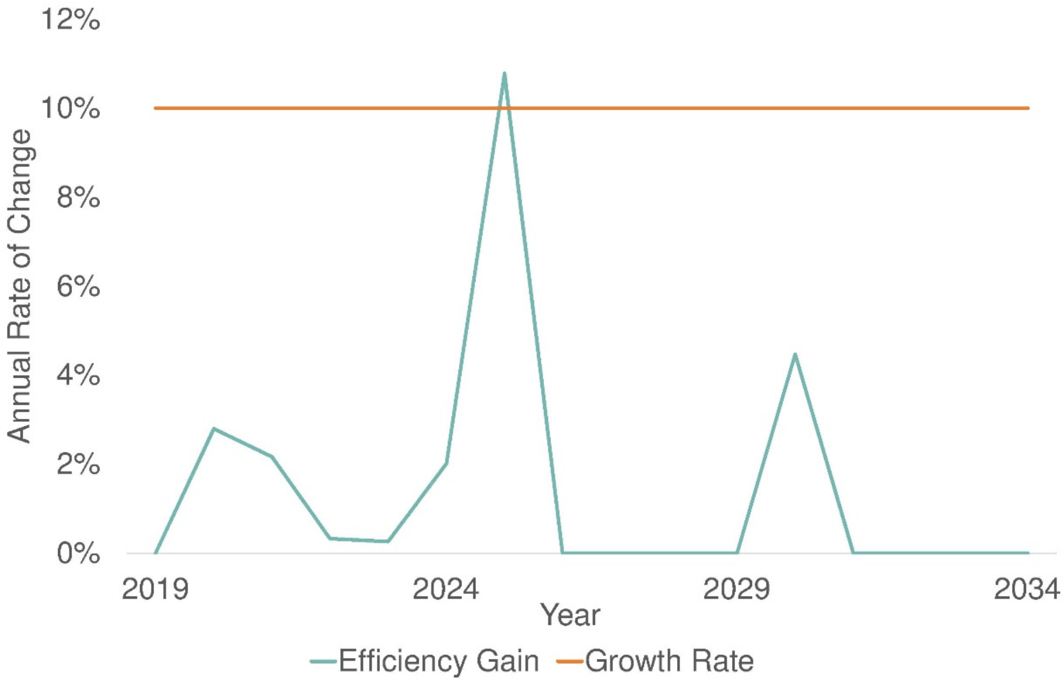


Figure 11. Tension between the assumed annual growth rate (orange) and the efficiency gains (blue) from implementing the product swaps as scheduled. The efficiency gains rely on the schedule of PSI implementation laid out in our recommended strategy.

The only instance of decreased overall GHG emissions was in 2025, when all midterm solutions were incorporated at once (Figure 11). The overall efficiency gain was 10.78% while the assumed growth rate remained constant at 10%. It is important to note, achieving this efficiency gain would require many major product changes all at once, which would be extreme changes for Patagonia to undergo, and therefore feasibility should be considered.

The proposed product swaps provided an immediate reduction in GHG emissions, but these savings could not compete with assumed growth over time. If Patagonia wants to realistically and significantly reduce company GHG emissions over time, product swaps alone would not provide enough emissions reduction to meet that goal. The tension between company growth and corporate emission reduction goals is a problem faced by all companies within the apparel industry.

6.4 Product Change Recommendation Scenarios

Due to the issue of product dependencies discussed earlier, not all product changes were included in the final recommendation, even if they provided a GHG emission reduction. Preceding and competing product swaps were incorporated into the recommendation after dependencies between product swaps were mapped to identify conflicts. When analyzing competing product dependencies, a decision was made deciding which product swap would be recommended over the other. The criteria for this decision depended on the GHG emissions of the two competing PSIs. The two product changes were compared and the PSI with the greatest reduction was chosen.

In addition to the team's final recommendation for product swaps, four other scenarios prescribed by Patagonia were analyzed. Scenario 1 included all product swaps that occurred in the near term plus two mid-term solutions. Scenario 2 included product swaps that impacted large categories of products in the mid and long term. Scenario 3 included product swaps that changed raw material to bio-based alternatives in the mid and long term. Scenario 4 included product swaps implementing alternative dye technologies in the mid and long term. It was assumed that because Scenarios 2-4 were implemented in the mid and long term periods, each subsequent scenario built upon product swaps implemented in Scenario 1. Therefore, GHG emission reductions achieved from product swaps implemented in Scenario 1 were accounted for in the emissions reductions calculated for Scenarios 2-4.

The graphs in the following section account for product dependencies and only include product changes that would be recommended.

6.4.1 Scenario 1- Near Term

For each scenario, the overall decrease in GHG intensity for the entire portfolio and emissions avoided compared to the counterfactual are shown. For the following sections, the first graph shows the overall GHG intensity change by implementing just Scenario 1 product swaps, as well as the additional reduction achieved by adding in the secondary scenario (either 2, 3, or 4). The second graph shows potential GHG emissions avoided compared to the counterfactual; highlighting incremental GHG savings provided by Scenario 1 product swaps, as well as the secondary scenarios when applicable.

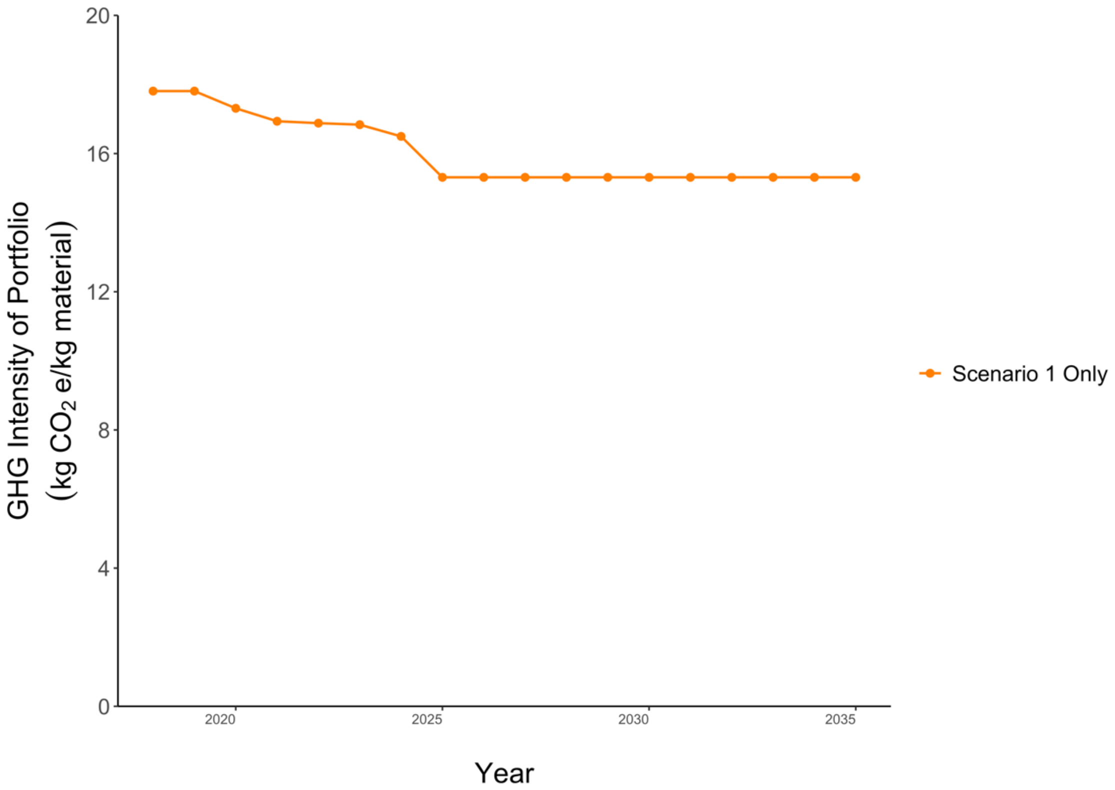


Figure 12. Overall decrease in greenhouse gas intensity for the entire portfolio by implementing Scenario 1 product swaps.

GHG intensity shown in the year 2017 is the GHG intensity of Patagonia's current product portfolio. In Figure 12, only Scenario 1 product swaps were implemented, which decreased overall GHG intensity of the portfolio by about 14%: a GHG intensity reduction of 17.81 $kgCO_2e/kg$ material in 2019 to 15.31 $kgCO_2e/kg$ material by 2035. Scenario 1 included changes that Patagonia already scheduled to implement over the next five years. These product changes yielded positive results to decrease overall company emissions by changing material and dye technologies for a few specific products.

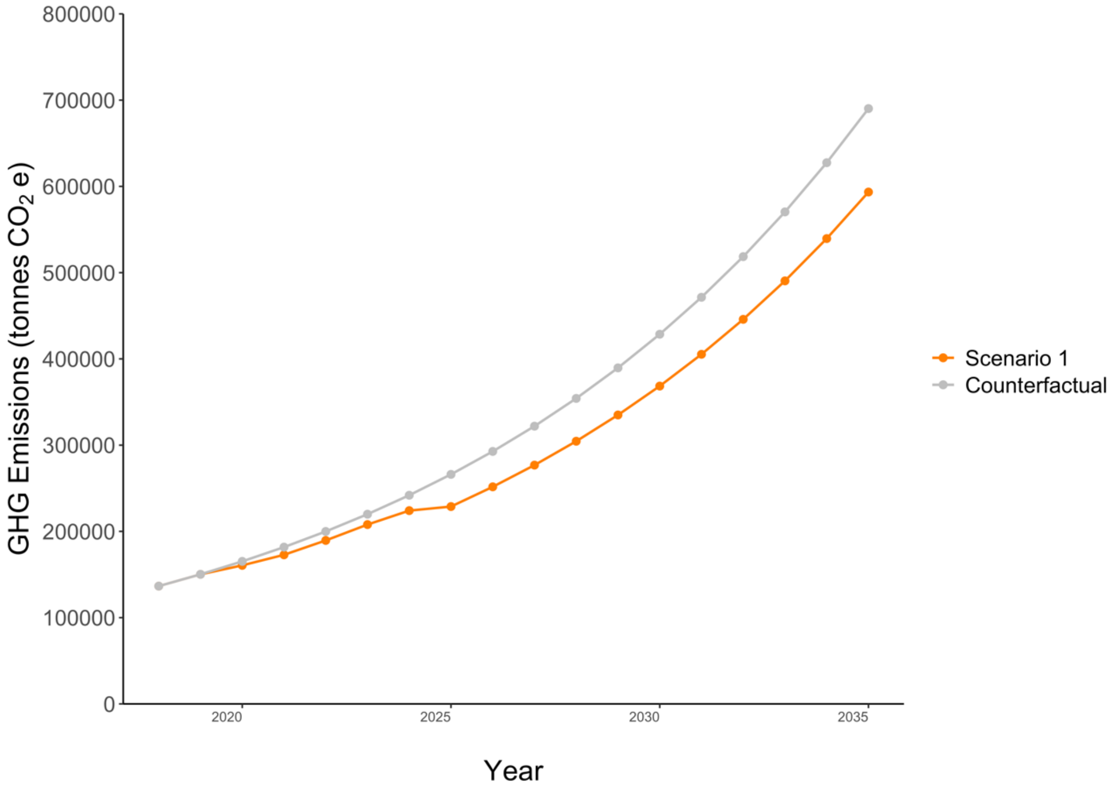


Figure 13. Greenhouse gas emissions saved by implementing Scenario 1 product swaps, compared to the counterfactual of business as usual with no product swap implementations.

Under the counterfactual, where Patagonia's product portfolio remained the same and all products maintained the same raw material and dye processes, GHG emissions increased over time following an assumed 10% growth trajectory. With Scenario 1 product changes, emissions continued to increase with the assumed 10% growth trajectory, but emissions would be less compared to the counterfactual (Figure 13). While the counterfactual emitted a total of about 5,660,000 tonnes CO_2e emissions from 2020-2034, Scenario 1 emitted about 5,012,000 tonnes CO_2e.

Emissions declined slightly between 2020 and 2024, but the largest emissions reduction occurred in 2025, with the implementation of PSI 1.2.1.1. This product change impacted all synthetic material in the product portfolio; switching to recycled content clearly had a large impact reducing overall company emissions.

6.4.2 Scenario 2- Large Category Shifts

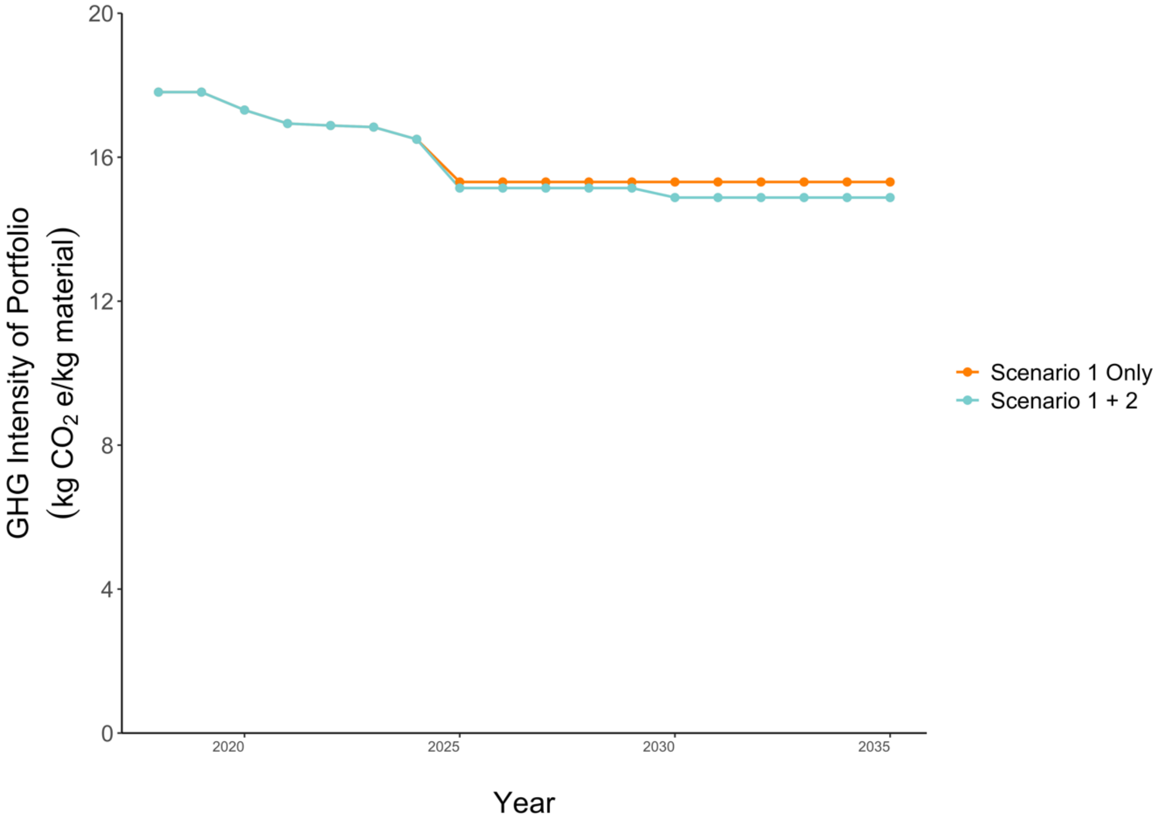


Figure 14. Overall decrease in greenhouse gas intensity for the entire portfolio by implementing Scenario 2 product swaps. Scenario 2 includes product swaps implemented in Scenario 1.

As was previously noted, PSIs included in Scenario 2 incorporated product dependencies and show product swaps that reduced GHG emissions. Scenario 2 included all product changes implemented in Scenario 1, as those product changes occurred in the near term. Scenario 2 product changes occurred in the mid-term and long term and therefore built upon Scenario 1.

Changes to large categories of product provided an additional reduction in the overall portfolio GHG intensity from 17.81 $kgCO_2e$/kg material in 2019 to 14.88 $kgCO_2e$/kg material by 2035, a 16% reduction (Figure 14). Large category shifts implemented in 2025 and 2030 greatly reduced overall company GHG intensity; however, these are large changes for Patagonia to implement, requiring massive product redesigns and buy-in from multiple stakeholders within the organization in order to execute.

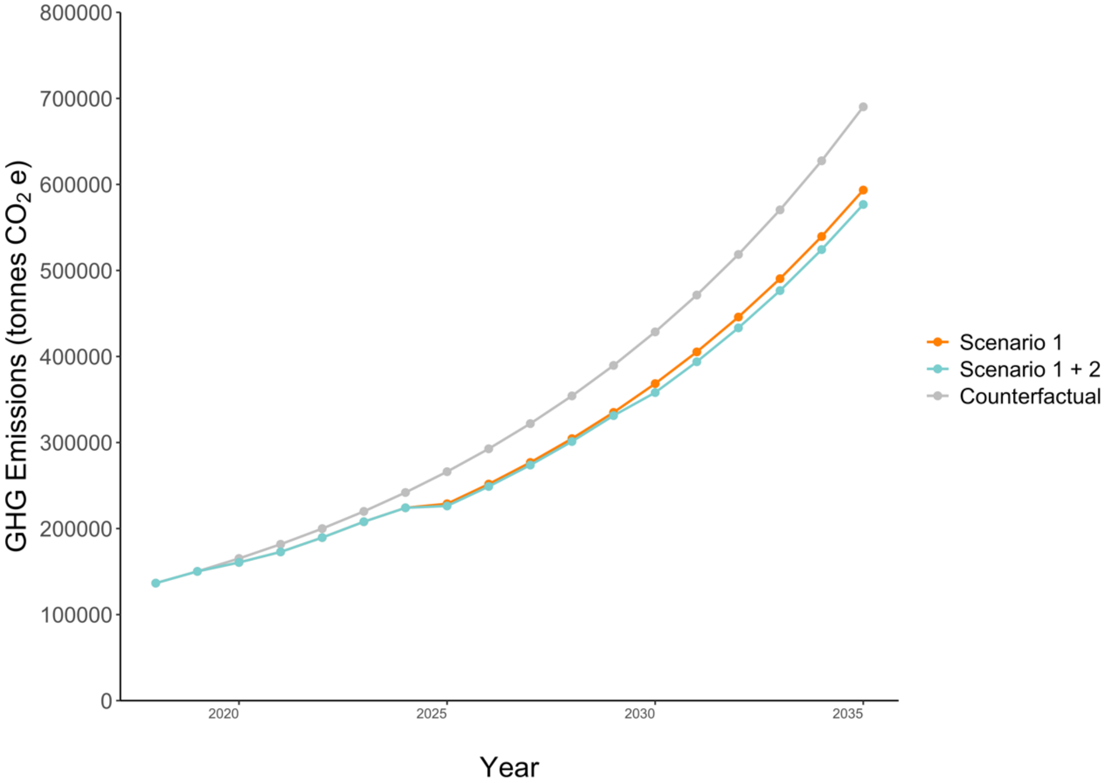


Figure 15. Emissions saved by implementing Scenario 2 product swaps, compared to the counterfactual of business as usual with no product swap implementations. Scenario 2 includes the savings from implementing Scenario 1 product swaps.

Most emissions savings result from Scenario 1 product changes, while the addition of Scenario 2 product changes reduced emissions only slightly more (Figure 15). Since Scenario 2 product changes occurred in the mid-term and long term, the additional reductions in emissions were seen in these two time periods. Total GHG emissions from 2020-2034 under the counterfactual were about 5,660,000 tonnes CO_2e, while Scenario 1 emitted 5,012,000 tonnes CO_2e. With the addition of Scenario 2 product swaps, there would be a savings of about 79,000 tonnes CO_2e, for total emissions of about 4,933,000 CO_2e from 2020-2034.

6.4.3 Scenario 3- Bio-based Materials

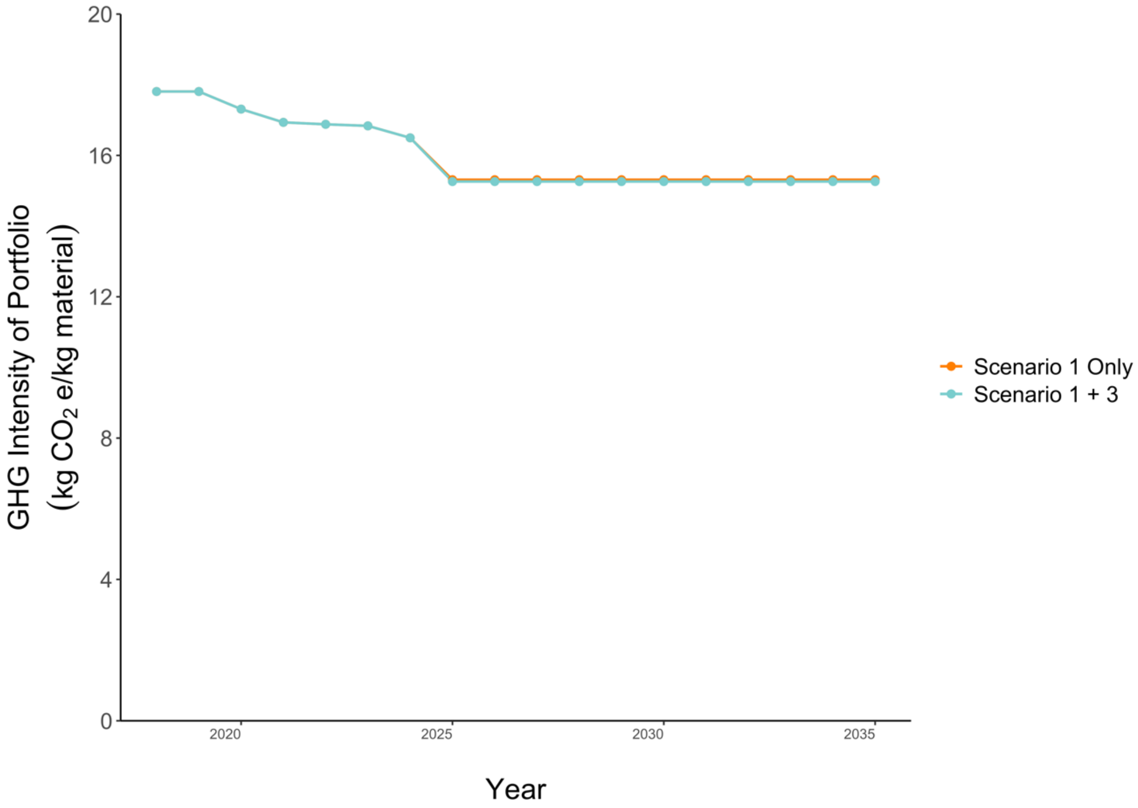


Figure 16. Overall decrease in greenhouse gas intensity for the entire portfolio by implementing Scenario 3 product swaps. Scenario 3 includes product swaps implemented in Scenario 1.

Due to the number of product dependencies in Scenario 3, there were only a few additional product swaps implemented in Scenario 3, which is why additional reductions in GHG intensity compared to Scenario 1 were not large. GHG intensity by 2035 decreased from 15.31 $kgCO_2e/kg$ material under Scenario 1 only to 15.26 $kgCO_2e/kg$ material under Scenario 3 (Figure 16).

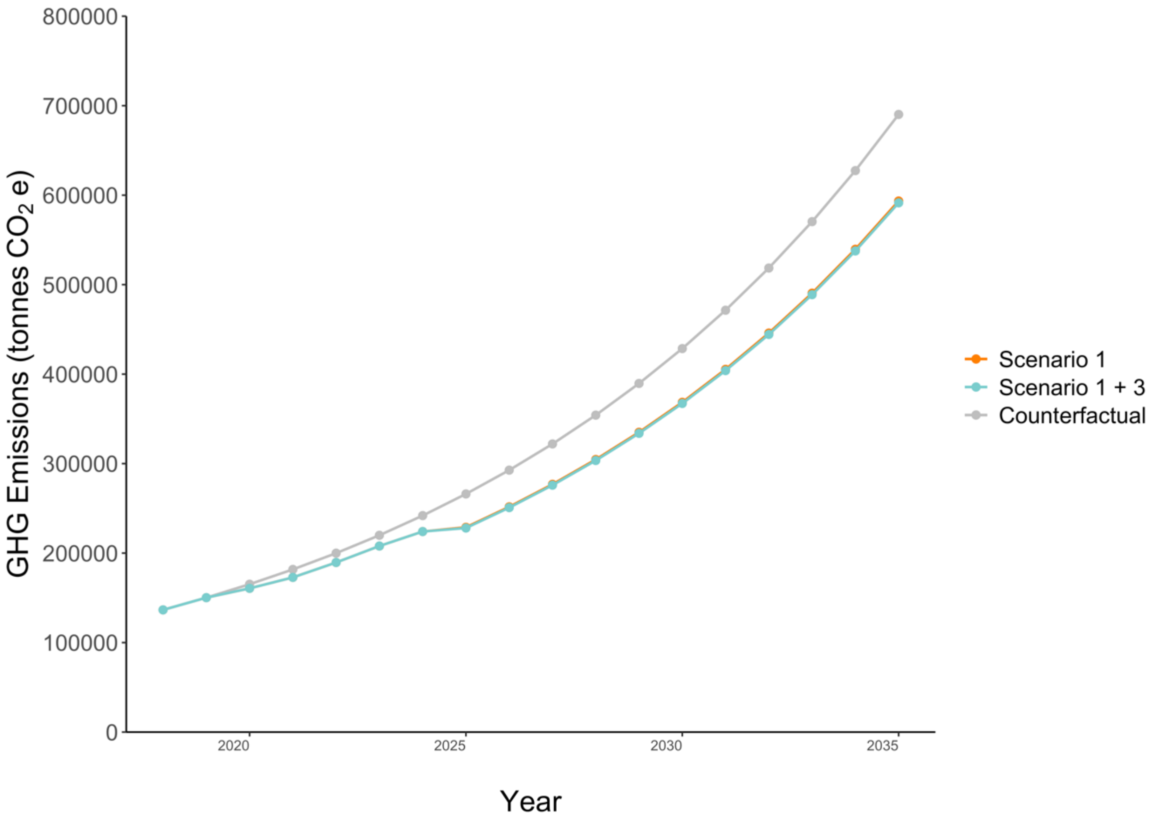


Figure 17. Emissions saved by implementing Scenario 3 product swaps, compared to the counterfactual of business as usual with no product swap implementations. Scenario 3 product includes the savings from implementing Scenario 1 product swaps.

For GHG emissions under Scenario 3, incremental changes compared to Scenario 1 were so small that Scenario 1 is barely visible in Figure 17. The two lines practically show the same values and are therefore indistinguishable. Scenario 1 emitted about 5,012,000 tonnes CO_2e, while Scenario 3 emitted about 5,000,000 tonnes CO_2e from 2020-2034. This would be a savings of about 12,000 tonnes CO_2e between Scenarios 1 and 2, but a savings of about 660,000 tonnes CO_2e compared to the counterfactual.

6.4.4 Scenario 4- Dye Technologies

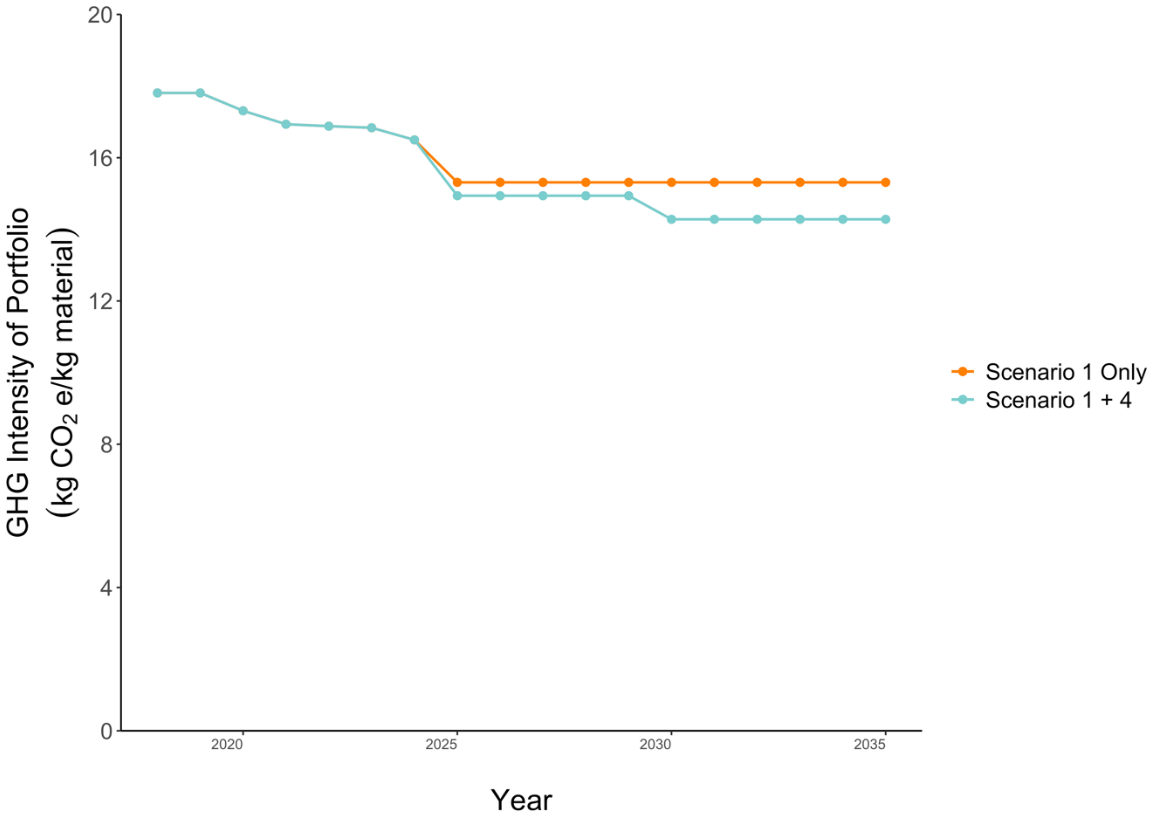


Figure 18. Overall decrease in greenhouse gas intensity for the entire portfolio by implementing Scenario 2 product swaps. Scenario 3 includes product swaps implemented in Scenario 1.

There were significant opportunities to reduce the overall portfolio GHG intensity through the implementation of dye technology shifts. Similar to the impacts seen when applying product changes to large categories of product, applying less-impactful dye technology to large categories of product yielded significant reductions in GHG intensity (Figure 18). These product changes were also implemented in the mid-term and long term, showing the large decreases at those two points on the timeline. The GHG intensity decreased from 17.81 kgCO_2e/kg material in 2019 to 14.28 kgCO_2e/kg material, nearly a 20% reduction in GHG intensity by 2035.

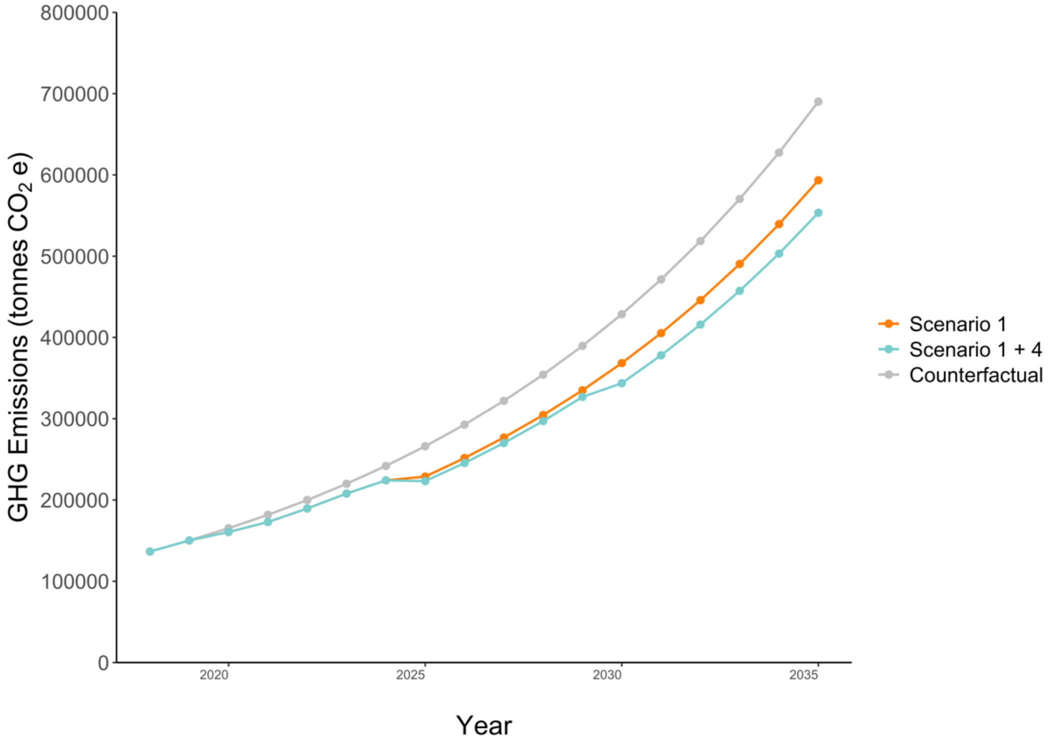


Figure 19. Emissions saved by implementing Scenario 4 product swaps, compared to the counterfactual of business as usual with no product swap implementations. Scenario 4 product includes the savings from implementing Scenario 1 product swaps.

GHG emissions from 2019-2034 under Scenario 4 were about 4,826,000 tonnes CO_2e, a potential savings of about 834,000 tonnes CO_2e compared to the counterfactual (Figure 19). For comparison, Scenario 1 alone emitted about 5,012,000 tonnes CO_2e. Therefore, implementing product swaps that apply impact-reducing dyes to large categories of Patagonia's product portfolio provide additional reductions in overall company GHG emissions.

6.4.5 Product Swap Recommendation

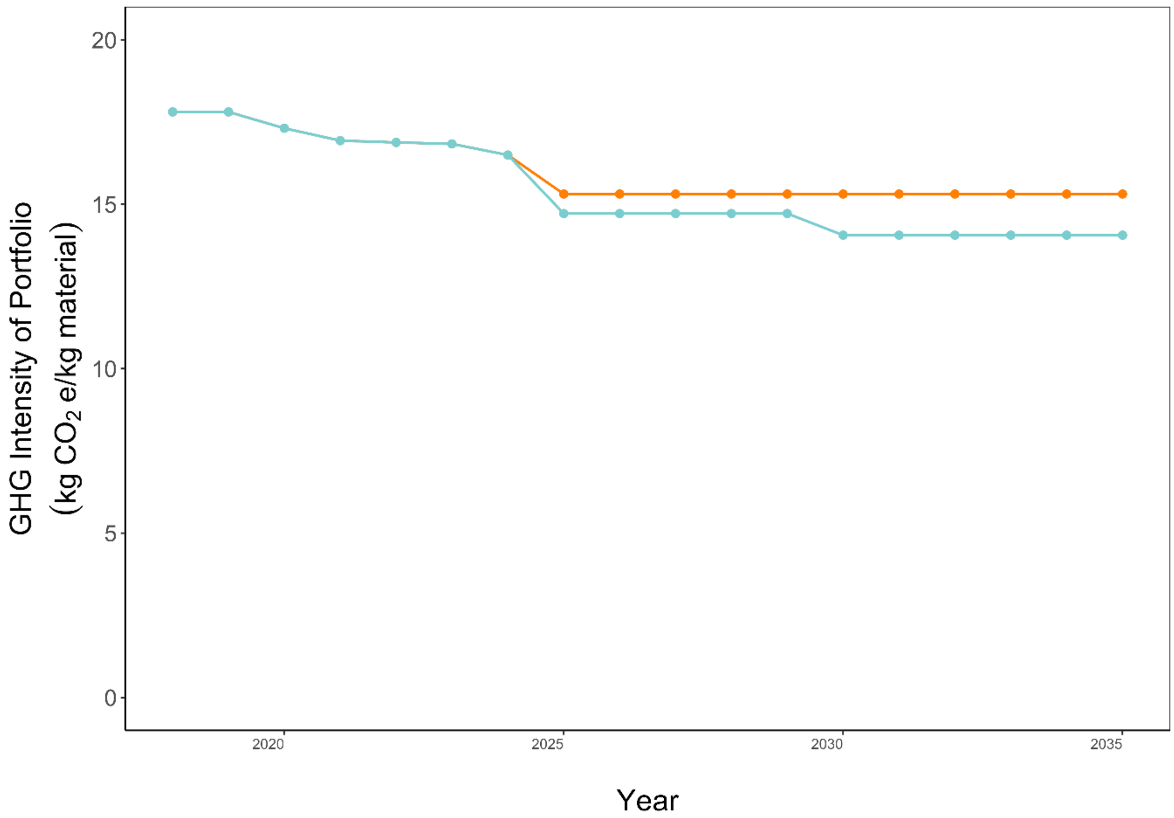


Figure 20. Overall decrease in greenhouse gas intensity for the entire portfolio by implementing the recommended strategy of product swaps. Includes PSI from all scenarios and accounts for all product dependencies.

Once the GHG reductions of each individual product swap were compared to the counterfactual and product dependencies were considered, a final recommendation strategy of product swaps was crafted. The recommended strategy included product swaps across all three time periods, including changes to both smaller collections of product, as well as large category shifts.

Through this collection of product swaps, the GHG intensity of the portfolio decreased from 17.81 $kgCO_2e/kg$ material in 2019 to 14.06 $kgCO_2e/kg$ material by 2035, a 21% reduction in GHG intensity. The full list of product swaps included in the recommended strategy is included in Appendix G.

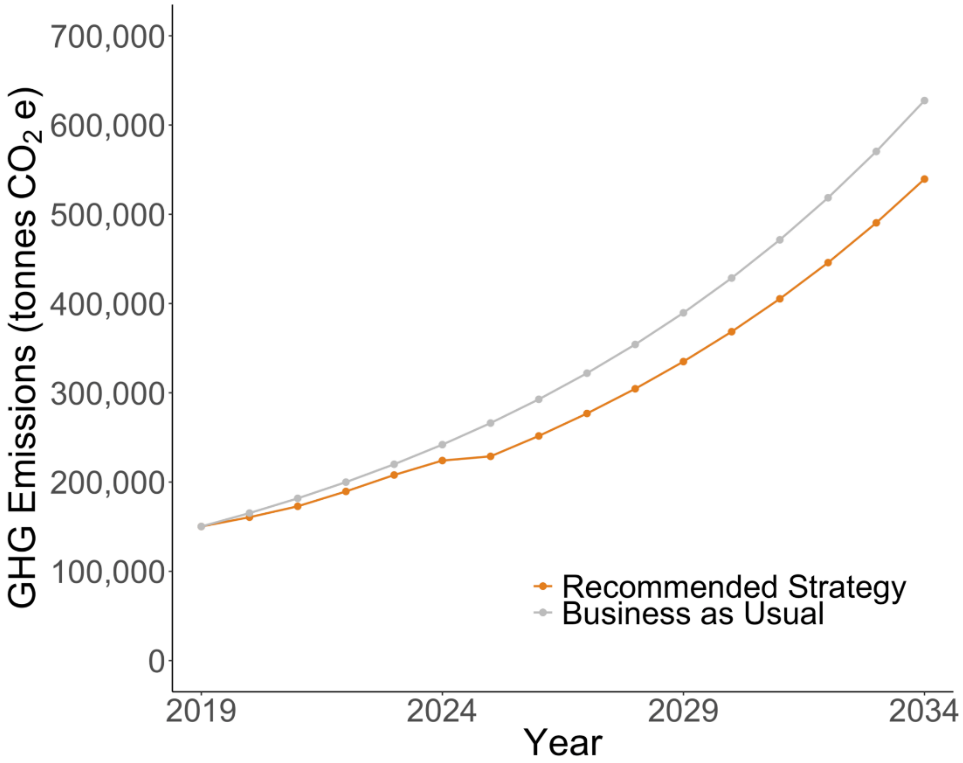


Figure 21. Emissions saved by implementing recommended strategy of product swaps, compared to the counterfactual of business-as-usual with no product swap implementations.

By implementing the recommended strategy, there would be a savings of about 886,000 tonnes CO_2e compared to the counterfactual over the period of analysis, 2020-2034 (Figure 21). Total GHG emissions would decrease from about 5,660,000 tonnes CO_2e in the counterfactual to about 4,774,000 tonnes CO_2e, resulting in about a 15% reduction in overall GHG emissions aggregated over the 15-year time period, compared to business as usual.

6.4.6 Maintaining Emissions at Current Levels

Finally, the team analyzed a strategy to hold Patagonia's current emission levels constant at the end of the 2020-2034 timeframe. The assumed 10% growth rate quickly overtook the efficiency gains generated from implementing product swaps and resulted in increased GHG emissions, therefore a growth rate that could keep emissions at 2019 levels was calculated. Assuming the GHG intensity of the overall product portfolio would decrease on the schedule prescribed by the recommended strategy, an annual growth rate of 1.58% resulted in emissions in 2034 equaling emissions in 2019 (Figure 22).

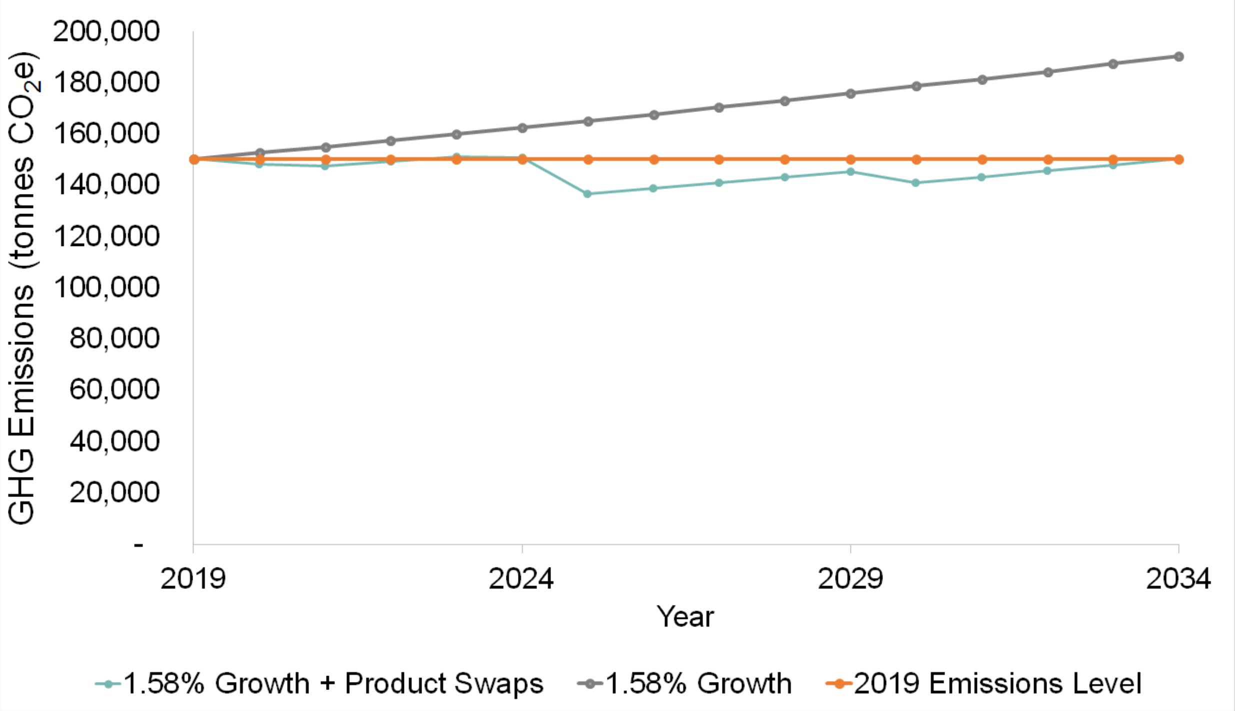


Figure 22. Emissions projected assuming an annual growth rate of 1.58%. Following the recommended strategy of implementing 31 product swaps results in emissions in 2034 being exactly equivalent to 2019 levels.

7.0 Discussion

7.1 Growth & Alternative Business Models for Emissions Reduction

The difficulty in achieving net reductions in GHG emissions lies in the tension between having economic success defined by annual growth and the limits of reducing GHG emissions through technological innovation, provided here by using less impactful technologies. Decreasing the rate of growth will slow the amount of GHG emissions over time, but will ultimately still lead to increases in GHG emissions. Even limiting company growth will only keep GHG emissions constant at the level when the growth rate was capped, but will not lead to reductions in GHG emissions.

As a way to counteract some of the GHG emissions impact associated with company growth, other business models exist that differ from the traditional apparel retail model. Clothing reuse programs are one option apparel companies are exploring as a way to achieve additional emissions reduction. Patagonia's Worn Wear program is an example of such a type of reuse program, where gently used products are resold at a discounted price. The assumption is that purchasing used garments offsets the purchase of some new garments, and therefore the emissions associated with the creation of a new garment. The reuse program gives the garment a second life and extends its use. A program like this could potentially reduce some of the emissions associated with company growth.

Rental programs are another option that apparel companies can adopt, where customers rent the pieces they need for a set time period and return them to be used by another customer. This model allows the company to make a profit, while reducing the number of virgin products sold. By shifting the buyer's choice away from a virgin product and toward a rental product, the emissions reduction occurs from avoiding the emissions associated with virgin product creation.

Due to the challenge company growth poses for emissions reduction, companies will need to adopt multiple strategies and programs to successfully reach ambitious GHG emission reduction targets. No one project or initiative alone will achieve such a goal, therefore a combination of efforts, such as reducing company growth, implementing materials innovation, powering supply chains with renewable energy, and creating reuse and rental programs are just some of the efforts companies can adopt to reduce overall company GHG emissions.

8.0 Conclusion

There is an opportunity in the product design phase to proactively address the environmental impact of apparel products using alternative materials and dyes. The difficulty in achieving net GHG emissions reduction lies in the tension between the rate of company growth and the rate of GHG savings for any mitigation strategy. In the corporate sector, there are inherent limits to counteracting GHG emissions through product design, especially when economic success is defined by annual growth. This problem applies not just to Patagonia, but across the apparel industry and nearly all facets of the economy.

While Patagonia can significantly reduce GHG emissions through the adoption of alternative materials and dyes, these efforts must be supplemented by other strategies to meet aggressive GHG reduction targets, such as science-based targets and carbon neutrality. These goal-setting frameworks are designed to drive massive GHG reductions, which simply cannot be achieved through product changes if companies continue to grow and sell more products. Nonetheless, addressing GHG emissions from textile production is a critical step for Patagonia and the apparel industry at large. Textile production accounts for 85% of Patagonia’s overall GHG emissions and other apparel companies likely contribute a similar amount. Directly addressing the primary driver of emissions is necessary to make significant and lasting change. Innovatively reducing GHG emissions from textile production, through material and dye changes or other strategies, are crucial steps for the apparel industry to be part of the solution in addressing global climate change.

9.0 References

Alberici, S., Boeve, S., Van Breevoort, P., Deng, Y., Förster, S., Gardiner, A., … Wouters, K. (2014a). *Subsidies and costs of EU energy: Annex 1-3*. Retrieved from http://ec.europa.eu/energy/en/content/final-report-ecofys

Alberici, S., Boeve, S., Van Breevoort, P., Deng, Y., Förster, S., Gardiner, A., … Wouters, K. (2014b). *Subsidies and costs of EU energy: Final report*. Retrieved from http://ec.europa.eu/energy/en/content/final-report-ecofys

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T., & Siebert, S. (2003). Development and testing of the WaterGAP 2 global model of water use and availability. *Hydrological Sciences Journal*, *48*(3), 317–338. https://doi.org/10.1623/hysj.48.3.317.45290

Bakker, K. (2014). The Business of Water: Market Environmentalism in the Water Sector. *Annual Review of Environment and Resources*, *39*(1), 469–494. https://doi.org/10.1146/annurev-environ-070312-132730

Beton, A., Dias, D., Farrant, L., Gibon, T., Le Guern, Y., Desaxce, M., … Boufateh, I. (2011). *Environmental Improvement Potential of Textiles (IMPRO-Textiles)*. *European Commission*. https://doi.org/10.2791/52624

Chen, L., Pelton, R. E. O., & Smith, T. M. (2016). Comparative life cycle assessment of fossil and bio-based polyethylene terephthalate (PET) bottles. *Journal of Cleaner Production*, *137*, 667–676. https://doi.org/10.1016/J.JCLEPRO.2016.07.094

Climate Action Strategy 2025. (2018). Retrieved from https://www.levistrauss.com/wp-content/uploads/2018/07/LSCO_Climate_Action_Strategy_2025.pdf

Companies Taking Action | Science Based Targets. (n.d.). Retrieved November 13, 2018, from https://sciencebasedtargets.org/companies-taking-action

Cushing, H., & Bartlett, N. (2017). How-To Guide To Corporate Internal Carbon Pricing. Retrieved from https://www.ecofys.com/files/files/cpu-2017-how-to-guide-to-internal-carbon-pricing.pdf

Ecolab. (2017). *Smart water management for business growth: Integrating water risk into business decision making*. Retrieved from https://www.waterriskmonetizer.com/how-it-works/methodology/

European Environment Agency. (2013). *Assessment of cost recovery through water pricing*. Retrieved from http://www.eea.europa.eu/publications/assessment-of-full-cost-recovery

Fahimnia, B., Reisi, M., Paksoy, T., & Özceylan, E. (2013). The implications of carbon pricing in Australia: An industrial logistics planning case study. *Transportation Research Part D: Transport and Environment*, *18*, 78–85. https://doi.org/10.1016/j.trd.2012.08.006

Fahimnia, B., Sarkis, J., Dehghanian, F., Banihashemi, N., & Rahman, S. (2013). The impact of carbon pricing on a closed-loop supply chain: an Australian case study. *Journal of Cleaner Production*, *59*, 210–225. https://doi.org/10.1016/J.JCLEPRO.2013.06.056

Gajjar, C. (2018). 4 Ways Companies Can Price Carbon: Lessons from India | World Resources Institute. Retrieved May 29, 2018, from http://www.wri.org/blog/2018/04/4-ways-companies-can-price-carbon-lessons-india

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). *Production, use, and fate of all plastics ever made*. Retrieved from http://advances.sciencemag.org/

Goedkoop M., S. R. (2000). The ecoindicator'99: a damage oriented method for life cycle impact assessment: methodology report.

Gürses, A., Açıkyıldız, M., Güneş, K., & Gürses, M. S. (2016). *Dyes and Pigments*. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-33892-7

Gurudatt, K., De, P., Rakshit, A. K., & Bardhan, M. K. (2015). Dope-dyed Polyester Fibers from

Recycled PET Wastes for Use in Molded Automotive Carpets. https://doi.org/10.1177/1528083705049053

Helling, R. K., & Russell, D. A. (2009). Use of life cycle assessment to characterize the environmental impacts of polyol production options. *Green Chemistry*, *11*(3), 380–389. https://doi.org/10.1039/b815833a

Hoekstra, A. Y., & Chapagain, A. K. (2011). The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences*, *15*(5), 1577–1600. https://doi.org/10.5194/hess-15-1577-2011

Internal Carbon Pricing | Center for Climate and Energy Solutions. (2019). Retrieved March 10, 2019, from https://www.c2es.org/content/internal-carbon-pricing/

IPCC. (2014). *Climate Change 2013. the Fifth Assessment Report* (Vol. 5).

Itsubo, N., Sakagami, M., Washida, T., Kokubu, K., & Inaba, A. (2004). Weighting across safeguard subjects for LCIA through the application of conjoint analysis. *The International Journal of Life Cycle Assessment*, *9*(3), 196–205. https://doi.org/10.1007/BF02994194

Jiang, Z., Ma, P., Guo, Z., Jia, Z., Pu, C., & Xiao, C. (2016). Effect of coupling agent on structure and properties of micro-nano composite fibers based on PET. *Journal of Applied Polymer Science*, *133*(34). https://doi.org/10.1002/app.43846

Kant, R. (2012). Textile dyeing industry an environmental hazard. *Natural Science*, *04*(01), 22–26. https://doi.org/10.4236/ns.2012.41004

Kering. (2013). *Kering Environmental Profit and; Loss (E P and L) Methodology 2013 Group Results*. Retrieved from http://www.kering.com/en/sustainability/methodology

Kering Integrated Report 2017. (2017). Retrieved from http://www.kering.com/sites/default/files/2017_kering_integrated_report_0.pdf

Kering Integrated Report 2018. (2018). Retrieved from https://keringcorporate.dam.kering.com/m/4685a5e3e2352d6e/original/Kering-Integrated-Report-2018.pdf

Kind, S., Neubauer, S., Becker, J., Yamamoto, M., Völkert, M., von Abendroth, G., … Wittmann, C. (2014). From zero to hero–Production of bio-based nylon from renewable resources using engineered Corynebacterium glutamicum. *Metabolic Engineering*, *25*, 113–123. https://doi.org/10.1016/j.ymben.2014.05.007

Kuczenski, B., & Geyer, R. (2011). *Life Cycle Assessment of Polyethylene Terephthalate (PET) Beverage Bottles Consumed in the State of California. State of California, Department of Resources Recycling and Recovery*. Retrieved from http://www.calrecycle.ca.gov/Publications/Detail.aspx?PublicationID=1487

Kuczenski, B., & Meisterling, K. (2016). *LCA comparison of bio-based, fossil, and recycled PET: Inventory Model and Results (v0.91)*.

Legatt, M. (2018). *White Paper on Nylon - PATAGONIA CONFIDENTIAL, May 31*. Ventura.

Liu, M., Shadbegian, R., & Zhang, B. (2017). Does environmental regulation affect labor demand in China? Evidence from the textile printing and dyeing industry. *Journal of Environmental Economics and Management*, *86*, 277–294. https://doi.org/10.1016/j.jeem.2017.05.008

McCann, J. (2015a). Environmentally conscious fabric selection in sportswear design. In *Textiles for Sportswear* (pp. 17–52). Elsevier Ltd. https://doi.org/10.1016/B978-1-78242-229-7.00002-3

McCann, J. (2015b). Environmentally conscious fabric selection in sportswear design. In *Textiles for Sportswear* (pp. 17–52). Elsevier Ltd. https://doi.org/10.1016/B978-1-78242-229-7.00002-3

Methods | Science Based Targets. (n.d.). Retrieved July 17, 2018, from https://sciencebasedtargets.org/methods/

Morris, J., Canzoneri, D. (1992). Comparative lifecycle energy analysis: theory and practice. *Resour. Recycl.* , (November), 25–30.

Murugesh, K. B., & Selvadass, M. (2013). *Life Cycle Assessment for the Dyeing and Finishing Process of Organic Cotton Knitted Fabrics*. *Article Designation: Refereed JTATM* (Vol. 8). Retrieved from http://stargate.cnr.ncsu.edu/index.php/JTATM/article/viewFile/3396/2268

Muthu, S. S., Li, Y., Hu, J. Y., & Mok, P. Y. (2012). Recyclability Potential Index (RPI): The concept and quantification of RPI for textile fibres. *Ecological Indicators*, *18*, 58–62. https://doi.org/10.1016/j.ecolind.2011.10.003

Natural Capital Coalition. (2016). *Natural Capital Protocol Principles and Framework*. Retrieved from https://naturalcapitalcoalition.org/protocol/

Parisi, M. L., Fatarella, E., Spinelli, D., Pogni, R., & Basosi, R. (2015). Environmental impact assessment of an eco-efficient production for coloured textiles. *Journal of Cleaner Production*, *108*, 514–524. https://doi.org/10.1016/J.JCLEPRO.2015.06.032

Patagonia Inc. (2005). *Patagonia's Common Threads Garment Recycling Program: A Detailed Analysis*. Retrieved from https://www.patagonia.com/pdf/en_US/common_threads_whitepaper.pdf

Pawelzik, P., Carus, M., Hotchkiss, J., Narayan, R., Selke, S., Wellisch, M., … Patel, M. K. (2013). Critical aspects in the life cycle assessment (LCA) of bio-based materials – Reviewing methodologies and deriving recommendations. *Resources, Conservation and Recycling*, *73*, 211–228. https://doi.org/10.1016/J.RESCONREC.2013.02.006

Pfister, S., Bayer, P., Koehler, A., & Hellweg, S. (2011). Environmental impacts of water use in global crop production: Hotspots and trade-offs with land use. *Environmental Science and Technology*, *45*(13), 5761–5768. https://doi.org/10.1021/es1041755

Pfister, S., Koehler, A., & Hellweg, S. (2009). Assessing the environmental impacts of freshwater consumption in LCA. *Environmental Science and Technology*. https://doi.org/10.1021/es802423e

Piemonte, V., & Gironi, F. (2011). Land-use change emissions: How green are the bioplastics? *Environmental Progress & Sustainable Energy*, *30*(4), 685–691. https://doi.org/10.1002/ep.10518

PUMA. (2018). Environmental Profit and Loss Account. Retrieved April 25, 2018, from http://about.puma.com/en/sustainability/environment/environmental-profit-and-loss-account

Quantis. (2018). MEASURING FASHION: Environmental Impact of the Global Apparel and Footwear Industries Study, 1–64. Retrieved from https://quantis-intl.com/measuring-fashion-report-2018/

Rupp, J. (2008). Ecology and Economy in Textile Finishing. *Textile World*.

Sandin, G., & Peters, G. M. (2018). Environmental impact of textile reuse and recycling – A review. *Journal of Cleaner Production*, *184*, 353–365. https://doi.org/10.1016/j.jclepro.2018.02.266

SGS Consulting. (2018). *Patagonia Greenhouse Gas Verification*.

Shen, L., Worrell, E., & Patel, M. K. (2010). Open-loop recycling: A LCA case study of PET bottle-to-fibre recycling. *Resources, Conservation and Recycling*, *55*(1), 34–52. https://doi.org/10.1016/j.resconrec.2010.06.014

Shen, L., Worrell, E., & Patel, M. K. (2012). Comparing life cycle energy and GHG emissions of bio- based PET, recycled PET, PLA, and man-made cellulosics. *Biofuels, Bioproducts and Biorefining*, *6*(3), 625–639. https://doi.org/10.1002/bbb

Steele, V. (2005). *Encyclopedia of Clothing and Fashion 1*. *Reference Reviews*. https://doi.org/10.1177/0022022103251753

Styles, D. (2018, October). Skunkfunk has Science Based Targets approved. *Ecotextile News*. Retrieved from https://www.ecotextile.com/2018103023825/fashion-retail-news/skunkfunk-has-science-based-targets-approved.html

Sustainable Apparel Coalition. (2016). *Higg Materials Sustainability Index (MSI) Methodology*. *msi.higg.org/page/msi-home*. Retrieved from http://msi.higg.org/page/msi-home

Sustainable Apparel Coalition - Higg MSI. (n.d.). Retrieved May 14, 2018, from https://msi.higg.org/page/msi-home

The World Bank. (2016). State and Trends of Carbon Pricing 2016. https://doi.org/10.1596/978-1-4648-1001-5

The World Bank. (2019). What is Carbon Pricing? | Carbon Pricing Dashboard. Retrieved March 6, 2019, from https://carbonpricingdashboard.worldbank.org/what-carbon-pricing

Thiemens, M. H., & Trogler, W. C. (1991). Nylon Production: An Unknown Source of Atmospheric Nitrous Oxide. *Science*, *251*(4996), 932–934. https://doi.org/10.1126/science.251.4996.932

Toprak, T., & Anis, P. (2017). Textile industry's environmental effects and approaching cleaner production and sustainability, an overview. https://doi.org/10.15406/jteft.2017.02.00066

Tsiropoulos, I., Faaij, A. P. C., Lundquist, L., Schenker, U., Briois, J. F., & Patel, M. K. (2015). Life cycle impact assessment of bio-based plastics from sugarcane ethanol. *Journal of Cleaner Production*, *90*, 114–127. https://doi.org/10.1016/J.JCLEPRO.2014.11.071

U-Long High Tech Textile Co., Ltd. (n.d.). Retrieved October 31, 2018, from https://www.u-long.com/en/index.php

van der Velden, N. M., Patel, M. K., & Vogtländer, J. G. (2014). LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane. *The International Journal of Life Cycle Assessment*, *19*(2), 331–356. https://doi.org/10.1007/s11367-013-0626-9

Vink, E. T. H., Rábago, K. R., Glassner, D. A., & Gruber, P. R. (2003). Applications of life cycle assessment to NatureWorks^{TM} polylactide (PLA) production. *Polymer Degradation and Stability*, *80*(3), 403–419. https://doi.org/10.1016/S0141-3910(02)00372-5

Weiss, M., Haufe, J., Carus, M., Brandão, M., Bringezu, S., Hermann, B., & Patel, M. K. (2012). A Review of the Environmental Impacts of Biobased Materials. *Journal of Industrial Ecology*, *16*, S169–S181. https://doi.org/10.1111/j.1530-9290.2012.00468.x

What is a science-based target? | Science Based Targets. (n.d.). Retrieved November 13, 2018, from https://sciencebasedtargets.org/what-is-a-science-based-target/

Wiloso, E. I., Heijungs, R., Huppes, G., & Fang, K. (2016). Effect of biogenic carbon inventory on the life cycle assessment of bioenergy: challenges to the neutrality assumption. *Journal of Cleaner Production*, *125*, 78–85. https://doi.org/10.1016/J.JCLEPRO.2016.03.096