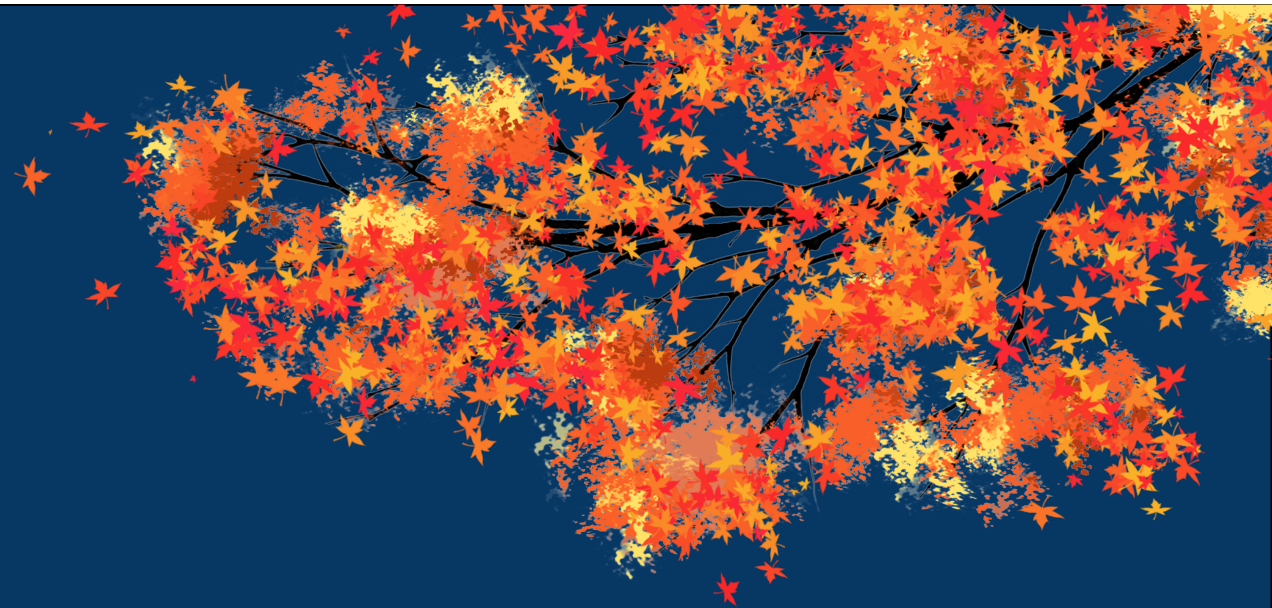

Life Cycle Assessment of Maple Syrup Production

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

University of Michigan
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EXECUTIVE SUMMARY

Maple syrup production, deeply rooted in North American tradition, faces increasing challenges from climate change. Despite its economic significance, the industry lacks a unified understanding of its environmental impact. In collaboration with the University of Michigan Center for Sustainable Systems and the North American Maple Syrup Council, our project aims to model the life cycle impact of maple syrup production. Through extensive literature review, interviews, data analysis, and systems modeling conducted between 2023 and 2024, we identified key areas of concern including climate change impacts, carbon offsets, distribution, packaging choices, and waste management. Our objective is to offer actionable insights empowering maple industry stakeholders to make informed decisions across the supply chain.

The first chapter outlines maple syrup producers' role in carbon sequestration and storage amidst climate change, addressing carbon accounting methods and the impact of climate change on syrup production. Recommendations for mitigation strategies are provided, emphasizing sap collection enhancement and forest maple silviculture practices.

In the second chapter, we discuss the downstream distribution modeling, a crucial aspect of the CSS Maple LCA. Analysis reveals the importance of quantifying downstream distribution metrics, particularly in assessing the sustainability of packaging materials like glass and high-density polyethylene (HDPE) bottles. Results indicate the environmental advantages of reusing packaging materials, especially HDPE bottles, and underscore the significance of transportation logistics in sustainability assessments.

The final chapter explores waste by-products generated within the sugarbush environment, focusing on plastic tubing waste from sap line replacement and permeate water from the Reverse Osmosis (RO) process. We discuss challenges associated with managing these waste streams and explore potential mitigation tactics within current and future waste management frameworks, including considerations for treating permeate as a system by-product rather than waste.

INTRODUCTION

Maple syrup has a long and rich history in North America. Maple tapping tradition was widespread among Native American tribes in the Northeast prior to European settlement, with stories of maple production appearing in myths from the Abenaki, Iroquois, and Mi'kmaq peoples (UVM, 2022). Today maple syrup and maple products are a large and growing global industry. Maple syrup's unique flavor, already a staple in many US and Canadian products, is becoming more popular in new markets in Europe and Asia. Maple syrup is also increasingly being marketed as a natural unprocessed sweetener for the health-conscious consumers (Atlantic Corporation Market Report, 2019).

In 2022 American sugar makers reportedly produced over 5.8 million gallons of syrup. Over 9,000 independent maple producers across the US collected, processed, and distributed this syrup to consumers across the globe (NASS, 2024). It is widely believed by industry experts that domestic production levels may be even higher, with this number being underestimated by as much as 30% (M. Farrell, personal communication, August 15, 2023). US-produced syrup was valued at nearly 216 million dollars in 2022 (NASS, 2024), comprising 20% of the global maple syrup market (Statista, 2023a).

As with many agricultural products, climate change is having a number of impacts on where and when maple syrup is produced. Maple tree sap only flows in very specific weather conditions when temperatures are mild during the day and drop below freezing at night. Sap does not start running when temperatures are too cold, and when it rises above 55 degrees Fahrenheit the sap begins to dry up. As such the US maple season typically only lasts between 25 and 40 days and has unpredictable start and end dates each season (NASS, 2024). Producers remain vigilant from January to April to make the most of each sugaring day when sap is flowing.

Producers are already seeing the impacts of climate change on sugaring timelines, with syrup seasons in many regions starting as early as December and ending by March (Rapp et. al. 2019). There is concern within some in the maple community that climate change will have long term impacts on where syrup can be sustainably produced. It renders some areas infeasible for long term maple syrup production and makes syrup production more common in areas where it was previously not viable. Another concern with a forestry product like maple syrup is vulnerability to wildfires, like the record-breaking blazes that burned across Canada in 2023. While hardwood trees like maple are typically less prone to burning than softwood conifers, a dramatic increase in wildfire frequency and severity could put maple forests at risk.

In recognition of the syrup production's unique vulnerabilities to the changing environment, the International Maple Syrup Institute (IMSI) is keen to better understand how the maple industry contributes to climate change. However, assessing the ecological footprint of the maple syrup industry poses a number of key challenges, chief among them a lack of visibility into the full maple supply chain.

The maple industry is highly fragmented, composed almost exclusively of small family-run businesses at the producer level. Certain small-scale sugarmakers still collect sap with metal taps and buckets, while the vast majority run more sophisticated operations involving plastic tubing, vacuum pumps, and high-end evaporators. Some producers swear by wood-fired evaporation as a marker of authentic sugar making while others use cutting-edge reverse osmosis technology to expedite the sap reduction process. Some operations are powered by the grid, and others run entirely on generators. Natural variability in topography and forest type can have huge impacts on the length and complexity of tubing networks. Of the thousands of sugarbushes in the United States, no two look exactly alike.

In 2022 The University of Michigan Center for Sustainable Systems, in collaboration with the North American Maple Syrup Council, began the process of disentangling this complex system and modeling the life cycle impact of maple syrup products. With funding from a USDA Acer grant the CSS project is working directly with producers to collect data on their operations, model the emissions of the most common production practices and parameters, and provide a footprint calculator that producers can use to assess the carbon footprint of their unique sugarbush. Currently, the project is working with its second cohort of producer recruits to build a comprehensive model of different production scenarios.

OUR CAPSTONE PROJECT

Our capstone project came together around the needs of both the Center for Sustainable Systems and the maple producer community. It both supplements and complements the research efforts of CSS, which focused largely on modeling an LCA from producer-generated primary data collection and upstream emissions. Our analysis provided a holistic picture of the maple industry impact landscape by focusing on downstream distribution, waste byproducts of production, packaging, and carbon cycling at the sugarbush.

While initially scoped as a quantitative analysis, our work was deeply informed by the qualitative stakeholder engagement process that the team engaged in over the Summer of 2023. It is critical to highlight that our project came together as a synthesis of supplier engagement and impact measurement. In the early stages of the Acer grant LCA, we worked with CSS on the producer recruitment phase of the data collection process. These conversations with trade association leaders, producers, packer-distributors, and Ag Extension maple specialists were pivotal; not only in better understanding the enormous variability of sugarbush size and operations, but also in designing a research plan that responded to the relevant needs and questions of the maple community.

During the engagement phase, we realized that an effective project would need to focus on both providing recommendations for environmental impact reduction and reducing barriers to the adoption of these recommendations. The maple community is tight-knit. There is a culture of information-sharing among producers at every level, from hobbyist sugar makers to full-time sugarbush operators. In maple trade conferences, state association meetings, Facebook groups, and online forums they discuss the best new equipment on the market or tricks for keeping the squirrels off their drop lines. As every sugarbush looks different, maple producers have a natural ingenuity and seemingly a solution for everything. For many producers, energy efficient technologies and practices were not novel ideas. What we observed was not necessarily a lack of awareness of solutions that could reduce emissions, but a lack of confidence in – and comfort with – new production methods. Therefore, the key for a successful Acer grant deliverable was not only an impact assessment tool and tailored recommendations, but also research that directly addressed the concerns of industry players hesitant to champion these solutions.

We also discovered that despite widespread knowledge of best practices in many aspects of the syrup value chain, there were some environmental topics where reliable information was scarce and consensus on best practices was low. From this outreach process and our collaboration with the CSS, our capstone team ultimately identified five major areas of focus in which institutional knowledge was lacking but community interest was high: climate change impacts on maple production; the future landscape and applicability of carbon offsets; the carbon footprint around downstream distribution; systems effects of packaging choices; and mitigation tactics for waste byproducts – specifically plastic waste and permeate water from reverse osmosis systems. Our team's goal is to provide valuable research and original analysis in these four areas, such that the maple industry players can make more informed decisions about production, packaging, distribution and disposal at every node of the maple supply chain.

Over the course of 2023 and 2024, our team engaged in a combination of literature review, interviews, data analysis and systems modeling to investigate these five research topics. Ultimately, this project is intended to provide insight and recommendations to the maple syrup community as they navigate a complex climate future.

In the first chapter we delve into the effects of climate change on maple tree productivity and explore strategies for resilience in a changing climate landscape. Chapter 1 begins with a discussion of carbon cycling in maple forests. This section discusses growing interest around carbon markets, key concerns around measuring carbon offsets, and guidance for best practices for producers looking to enter these markets. This chapter concludes with an overview of three major climate-related threats to maple syrup production and strategies for mitigating these risks.

Chapter 2 focuses on modeling upstream and downstream impacts of the maple syrup value chain. The first part of this study models the downstream distribution of maple syrup from sugar shacks concentrated in the Northeast to homes and restaurants across the United States. This chapter then takes a closer look at packaging materials as one of the key variables from this model. Through a Life Cycle Assessment, we explore the systems impacts of glass and plastic packaging options for maple syrup products as well as the emissions reduction potential of localized bottle take back programs. Chapter 2 wraps up with recommendations for both producers and packer-distributors as they think through packaging and logistics decisions.

Chapter 3 looks at two key waste streams of the maple syrup production process: plastic waste and reverse osmosis permeate water. This section explores the challenges involved with measuring and managing these waste streams. We then dive into mitigation tactics for each of these waste by-products both in the present, and looking into the future.

CHAPTER 1

SECTION 1. CARBON & MAPLE FOREST

Sugarbushes, ranging from intimate clusters of 5 to 10 trees along a stonewall to expansive forests with hundreds of thousands of maple trees, represent not only a source of maple sap but also a nexus of ecological and cultural significance (D'Amato et al., n.d.). Maple-rich landscapes provide more than just firewood and maple syrup; they offer a plethora of ecosystem services essential for environmental balance. These services include water management, wildlife habitat provision, and recreational opportunities (D'Amato et al., n.d.). However, one of their most crucial functions is their role in climate regulation through carbon sequestration and storage. By absorbing carbon dioxide from the atmosphere, these forests actively contribute to the creation of what scientists term "forest carbon," a key component in mitigating climate change and maintaining ecological health (D'Amato et al., n.d.). This process highlights the indispensable role of maple-laden landscapes in sustaining both local ecosystems and global environmental stability.

I. Carbon Cycle in Maple Trees

Maple trees, like all forest vegetation, play a pivotal role in the carbon cycle. They act as vital carbon sinks, absorbing carbon dioxide from the atmosphere during photosynthesis and converting it into organic matter. This carbon becomes stored within various components of the tree, such as leaves, wood, and other organic materials, constituting roughly half of the forest's total biomass (Catanzaro and D'Amato, n.d.).

The carbon cycle begins with photosynthesis, as trees harness carbon dioxide, water, and sunlight to produce carbon-based sugars, simultaneously releasing oxygen into the atmosphere as a byproduct. While trees utilize these sugars for metabolic processes and growth, the allocation of carbohydrates between growth and respiration varies depending on factors such as species, age, and environmental conditions. Trees possess a remarkable capacity to store carbon in their wood, which accounts for about 50% of their dry weight and is rich in carbon-based compounds like cellulose, hemicellulose, and lignin (Kosiba, 2021). When a tree dies and decomposes or is burned, carbon dioxide is released back into the atmosphere, albeit at varying rates. However, this carbon can be reabsorbed by another tree, perpetuating the cycle of carbon storage and release, as depicted in Figure 1.

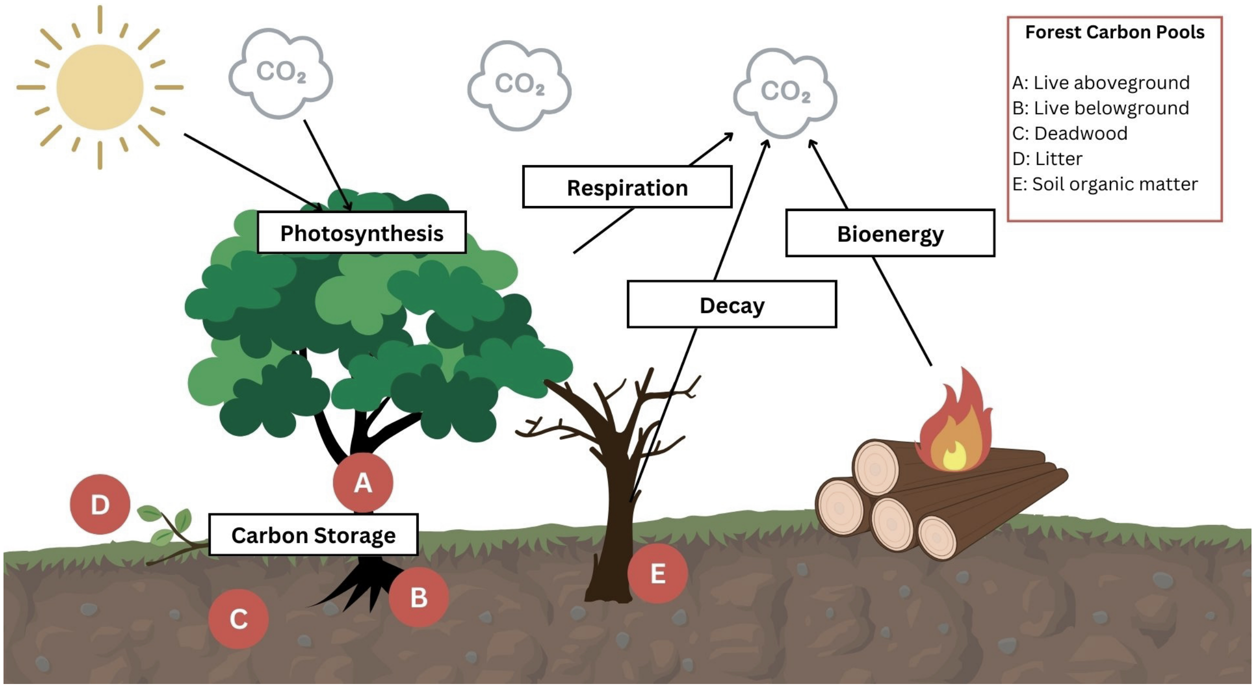


Figure 1. Carbon Cycle and Carbon Pools

Within the forest ecosystem, carbon is distributed among several pools, referred to as carbon pools. These pools include live aboveground and belowground biomass, deadwood, litter, and soil organic matter (Catanzaro and D'Amato, n.d.):

- Live aboveground (trees, shrubs, and other plants)
- Live belowground (roots)
- Deadwood (standing dead trees [snags] and downed logs)
- Litter (leaves, needles, and small branches)
- Soil organic matter (organic material in the soil, such as dead and decayed biomass [e.g., plant material and insects])

Each carbon pool serves as a reservoir for carbon storage with different rates of accumulation and decomposition over time. Figure 2 illustrates the average carbon stored within different pools for 80- to 100-year-old northern hardwood forests across New England (D'Amato et al., n.d.)

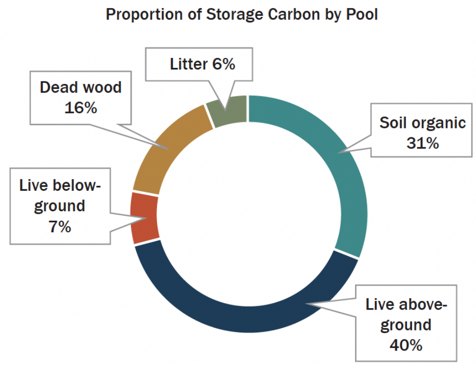


Figure 2 shows the average carbon storage in various pools for 80- to 100-year-old northern hardwood forests throughout New England (D'Amato et al., n.d.).

Carbon sequestration is the process through which forests absorb carbon dioxide from the atmosphere, primarily via photosynthesis, aiding in the maintenance and expansion of forest ecosystems. While the rate of carbon sequestration varies depending on factors such as forest age and environmental conditions, forests in the northeastern United States typically exhibit peak sequestration rates during their early to middle stages of growth, typically between 30 to 70 years old (Catanzaro and D'Amato, n.d.).

Carbon storage within forest ecosystems encompasses the total amount of carbon retained within various carbon pools over time. As forests mature, their capacity for carbon storage increases. Older forests generally demonstrate higher levels of carbon retention compared to younger counterparts.

Carbon emissions, on the other hand, represent the release of CO_2 into the atmosphere, contrasting with carbon sequestration, which involves the absorption of CO_2 by forests. Forest carbon can be re-emitted through processes like decomposition, respiration, or combustion, contributing to carbon emissions. The rate of carbon emissions is expressed as a positive number per unit of time, as it leads to an increase in atmospheric CO_2 levels (Kosiba, 2021).

The net carbon flux in a forest ecosystem takes into account both carbon sequestration and emissions, indicating the change in carbon storage over time. When carbon flux is negative, the forest functions as a carbon sink, sequestering more CO_2 than emitted, thereby increasing carbon storage. Conversely, when carbon flux is positive, the forest acts as a carbon source, emitting more CO_2 than absorbed, resulting in a decrease in carbon storage (Kosiba, 2021). This shift can occur due to factors such as land clearing, fire, or reduced carbon sequestration capacity due to environmental stressors. However, if the forest regenerates, it can resume its role as a carbon sink.

When examining carbon dynamics within forest ecosystems, it's crucial to recognize the variability observed both at the individual tree level and the broader forest level. According to Kosiba (2021), maple trees provide an illustrative example of these dynamics.

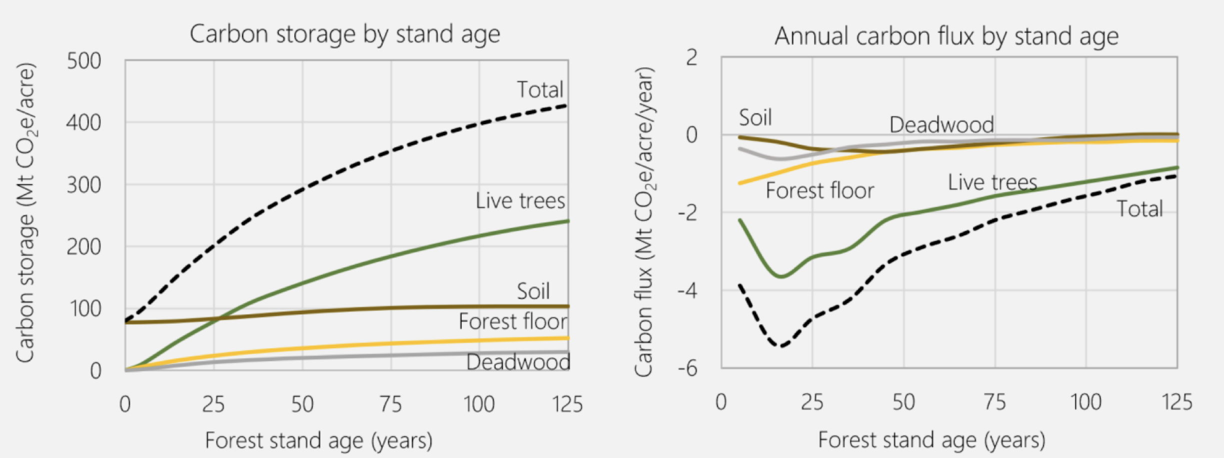
At the individual tree level, factors such as tree species, size, and overall health significantly influence its capacity to sequester and store carbon. Larger trees exhibit notably higher levels of carbon sequestration and storage compared to smaller ones. For instance, a single sugar maple tree with a trunk diameter of 10 inches stores approximately 0.75 Mt CO_2e, while a larger sugar maple with a 20-inch diameter can store up to 4 Mt CO_2e, around five times more carbon than its smaller counterpart.

Similarly, incremental growth in diameter yields differing carbon sequestration outcomes. A 10-inch tree gains a quarter of an inch in diameter to reach 10¼ inches sequesters and stores an additional 0.04 Mt CO_2e. In contrast, if the 20-inch tree also grows a quarter of an inch, it sequesters and stores an additional 0.1 Mt CO_2e—more than twice the amount of the smaller tree. This discrepancy arises from the larger tree's greater wood volume in the trunk, bark, branches, and roots (Kosiba, 2021).

At the forest level, variability in carbon storage and sequestration is influenced by numerous factors, including tree density, species composition, weather conditions, natural disturbances, human interventions like logging, and soil characteristics such as texture, drainage, and historical land use. Forests boasting diverse tree species and sizes, deep litter layers, undisturbed soils, and abundant deadwood typically harbor more carbon. Colder climates tend to host more carbon in soil and deadwood due to slower decomposition rates compared to warmer regions (Kosiba, 2021).

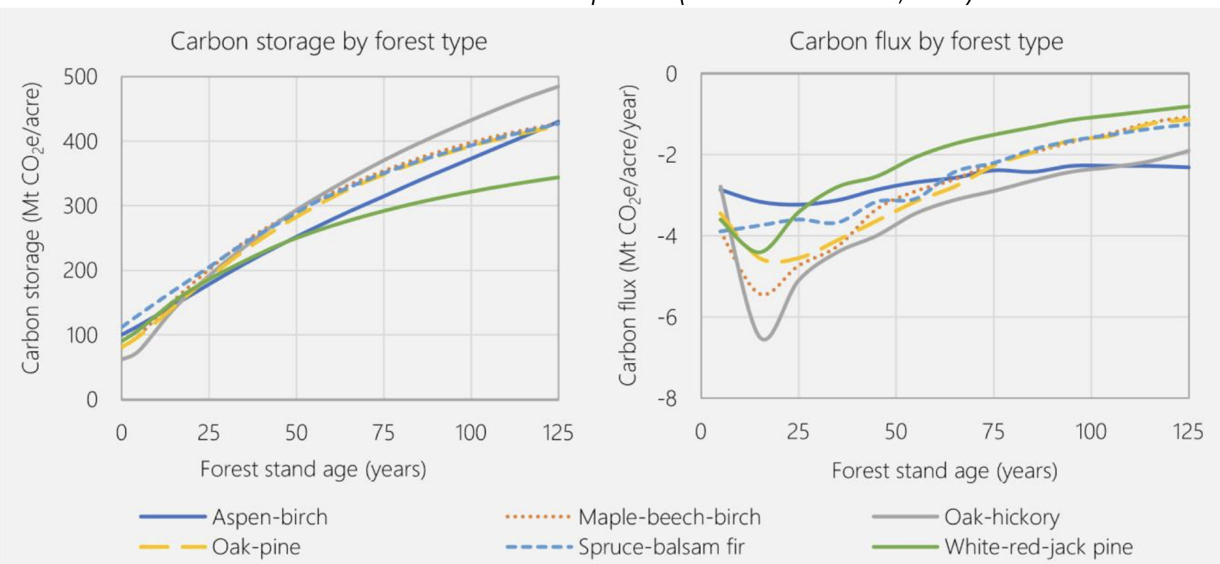
In general, individual hardwood trees store more carbon than softwood (conifer) trees of the same size due to the denser wood of hardwoods (Kosiba, 2021). Nonetheless, differences in carbon storage among forest types become evident when considering various carbon pools. For example, spruce-fir forests can accumulate significant carbon in the litter and soil pools because the needles of spruce and fir decompose slowly on the forest floor, facilitating carbon buildup (Kosiba, 2021).

In Figures 3 and 4, it's apparent that carbon storage increases across all forest types and carbon pools as the stand ages. The rate of carbon sequestration, as depicted by carbon flux, illustrates that younger forests typically sequester carbon at a faster pace, albeit with considerable variation among forest types and ages. Figure 3 delineates the differences in carbon pools, while Figure 4 identifies distinct forest types, such as oak-hickory forests, which store more carbon compared to others, such as white-red-jack pine forests.



Carbon storage (left) increases as a forest ages and if there are no significant disturbances or stressors. Carbon flux (right, negative values indicate carbon sequestration) shows a different pattern by stand age. For this maple-beech-birch forest, carbon sequestration peaks when the stand is 15-20 years[1].

Figure 3 shows how forest stands relate to carbon storage and annual carbon flux across various carbon pools (D'Amato et al., n.d.)



Forest of different types have similar patterns of carbon storage (left), although differences become more pronounced as forests age. Carbon flux (right, negative values indicate carbon sequestration) shows more pronounced differences among forest types when stands are young[10].

Figure 4 shows how forest stands relate to carbon storage and annual carbon flux across various forest types (D'Amato et al., n.d.).

Maple forests are increasingly acknowledged as essential carbon sinks, capable of gradually accumulating carbon over the years. Given the exacerbation of carbon emissions and atmospheric CO_2 levels due to climate change, preserving and expanding maple tree populations can serve as a significant strategy to mitigate its impacts. By efficiently capturing and storing carbon from the atmosphere, maple trees play a crucial role in combating climate change. Consequently, safeguarding maple trees and their habitats becomes increasingly imperative for upholding ecosystem health and resilience in the face of environmental challenges posed by climate change.

II. Forest Management and Carbon Dynamics

Given the crucial role that maple forests play in climate change scenarios, presented below are management strategies summarized from D'Amato (n.d.), a professor from the University of Vermont. Forest management practices wield a substantial impact on carbon dynamics within forest ecosystems. By modifying vegetation structure, species composition, and carbon pools, these practices can either enhance or diminish the capacity of forests to sequester and store carbon. Here, we delve into the diverse ways in which forest management influences carbon dynamics, encompassing both passive and active management strategies.

a. Passive Management Approach

Passive forest management entails minimal intervention, allowing natural processes to govern forest development. While this approach maintains high carbon storage and ongoing sequestration, it may result in lower sequestration rates relative to younger or multi-aged stands. Furthermore, the high stocking density associated with passive management can lead to reduced tree vigor, lower species diversity, and limited habitat values for wildlife.

b. Active Management Approach

Active forest management involves deliberate interventions to optimize carbon storage and sequestration. By strategically harvesting trees and manipulating stand structure, managers can influence carbon pools and enhance ecosystem resilience. For example, carbon-informed silvicultural practices aim to minimize carbon storage losses during harvest, particularly in aboveground and litter pools. Additionally, managing for large tree carbon storage and promoting species like sugar maple, yellow birch, and red oak can bolster carbon stocks while maintaining habitat quality and biodiversity.

c. Integrating Passive and Active Approaches

Forest managers often employ a combination of passive and active management strategies to achieve desired carbon outcomes. By retaining mature trees while selectively harvesting and promoting the growth of large carbon-rich species, managers can optimize carbon storage and sequestration across multiple spatial scales. Furthermore, controlling invasive species and preserving ecosystem diversity are crucial for sustaining long-term carbon stocks and ecosystem resilience.

d. Additional Considerations

Harvesting trees for various purposes, such as lumber or firewood, removes carbon from the forest. However, if the forest remains intact, other trees quickly occupy the space and sequester carbon as they grow. Moreover, using harvested wood for long-lived products, such as buildings or furniture, locks in carbon for the duration of the product's life (Kosiba, 2021). Additionally, forest management practices can facilitate the transfer of carbon from living biomass to dead wood, litter, and soil pools, enhancing ecosystem functions and biodiversity.

III. Carbon Accounting

Once we grasp the intricacies of the carbon cycle within maple forests, the next natural inquiry is the quantification of carbon storage. Understanding precisely how much carbon can be sequestered allows for informed decision-making and effective management practices. Equally important is the assessment of carbon offsetting, a crucial aspect for participation in carbon markets. However, carbon accounting and subsequent verification processes encounter numerous challenges. Hence, in the following sections, we will explore common carbon accounting methods applicable to maple forests, along with insights into carbon markets. Additionally, we will delve into the specific challenges that maple syrup producers face when seeking participation in these endeavors.

a. Forest Inventory Analysis (FIA) database

The quantity of carbon stored in living woody biomass varies significantly, influenced by factors such as tree species, stand density, silvicultural management, and tree age. Accessible through the USDA Forest Service, the Forest Inventory Analysis (FIA) database (Hoover et al., 2021) provides estimates of carbon storage per acre in the United States, utilizing data on tree species and geographical location. The US Forest Service's "carbon lookup tables" derive from FIA data and offer insights into forest carbon values categorized by region, forest type, and stand age.

Establishing a baseline is pivotal for distinguishing between the "business-as-usual" carbon storage and additional carbon storage eligible for sale in the market. For example, in reforestation projects, the baseline carbon amount is considered zero since no trees were initially present, underscoring the potential for significant carbon sequestration gains.

Numerous standards are available to facilitate the disclosure of sustainability practices and the establishment of targets within the maple syrup industry.

b. SBTi - Forest, Land and Agriculture (FLAG)

The Science-Based Targets initiative's Forest, Land, and Agriculture (FLAG) Guidance (Science Based Target, 2023) represents a groundbreaking framework for companies operating in land-intensive sectors, including the maple syrup industry, to set science-based targets that encompass land-based emission reductions and removals. This guidance is designed to address the significant role of the forest, land, and agriculture sector in global greenhouse gas emissions, which accounts for nearly a quarter of emissions worldwide, making it the second-largest emitting sector after energy.

The FLAG Guidance aims to empower companies with land-intensive operations to take effective action against climate change by incorporating land-based emissions reductions and removals into their sustainability strategies. By aligning with the Paris Agreement's goal to limit global warming to 1.5°C, the FLAG Guidance sets out key requirements for companies to set near-term and long-term science-based targets that prioritize emission reductions and removals from land-based activities.

Key requirements outlined in the SBTi FLAG Guidance include:

- Setting near-term FLAG science-based targets: Establishing 5-10 year emission reduction targets aligned with limiting warming to 1.5°C.
- Accounting for removals in near-term FLAG science-based targets: Incorporating biogenic CO_2 removals from activities such as ecosystem restoration, forest management improvements, silvopasture deployment, and soil carbon sequestration.
- Setting long-term FLAG science-based targets: Committing to reducing at least 72% of emissions by 2050 for companies with significant activities in the land and agriculture sectors, utilizing the SBTi Net-Zero Standard.
- Implementing zero deforestation targets: Setting targets to achieve zero deforestation by 2025, aligned with the Accountability Framework initiative.
- Setting science-based targets for fossil emissions: Requiring companies with land-based emissions to set science-based targets for both land-based and fossil emissions.

By adhering to the SBTi FLAG Guidance, maple syrup producers can play a vital role in mitigating climate change, preserving forest ecosystems, and contributing to a sustainable future for the industry and the planet.

c. Greenhouse Gas Protocol (GHG Protocol)

The GHG Protocol, a widely recognized framework for measuring and managing greenhouse gas emissions, is instrumental in guiding sustainability efforts within the maple syrup industry. In addition to its established methodologies for emissions accounting, the GHG Protocol is poised to further enhance its relevance with the forthcoming Greenhouse Gas Protocol Land Sector and Removals Guidance (GHG Protocol, 2023).

This new guidance, expected to be finalized by mid-2024, is tailored to assist companies in tracking and reporting GHG emissions and removals associated with land management activities, CO_2 removals, and biogenic products. By integrating these aspects into the broader GHG accounting framework, maple syrup producers will gain a more comprehensive understanding of their carbon footprint, including emissions and removals from land-based activities.

IV. Carbon Markets

a. Introduction of Carbon Credit, Carbon Offset and Carbon Market

Carbon credits and carbon offsets are often used interchangeably, but they carry distinct meanings. Carbon credits, also referred to as carbon allowances, are permissions for emissions issued primarily by governmental bodies (Constellation, n.d.). For instance, California operates its carbon market, granting credits to residents based on their energy consumption. Companies that obtain carbon credits gain authorization to emit one ton of CO_2 with the option to sell surplus credits. These credits are typically tied to emission reduction targets and are traded primarily among companies and nations as mandated by law. In regulated markets, cap-and-trade programs, overseen by regulatory authorities, set carbon emission limits known as the 'cap.' Over time, this cap decreases, challenging businesses to remain within their allocated emission limits. Participation in cap-and-trade programs is generally mandatory, with clear frameworks for emission reduction in place (Flowcarbon, n.d.).

On the other hand, carbon offsets enable the transfer of carbon revenue between companies, compensating for emissions through investments in green projects. These projects can be natural, like reforestation, or mechanical, such as renewable energy initiatives. Unlike carbon credits, creating offsets is voluntary and can be undertaken by anyone, even on a small scale (Constellation, n.d.). Purchasing carbon offsets in the Voluntary Carbon Market allows entities to effectively reduce their CO_2

equivalent emissions. The Voluntary Carbon Market (VCM) is a platform where individuals, corporations, and project developers voluntarily purchase and trade carbon offsets to balance their carbon emissions (Flowcarbon, n.d.). Unlike the regulated market, there are no regulatory mandates for companies to purchase offsets in this market. Participation in the VCM goes beyond legal requirements, offering opportunities for entities to offset emissions challenging to eliminate entirely. While smaller than the compliance market, the VCM is expected to see substantial growth (Flowcarbon, n.d.), with companies like Apple, Stripe, Shell, and British Petroleum actively seeking to offset their carbon footprint in this market (Constellation, n.d.). Though participation is voluntary, organizations are encouraged to invest in approved programs to demonstrate environmental commitment and avoid accusations of "greenwashing."

While both carbon credits and offsets represent the emission of one ton of carbon, it's essential to clarify that this measurement refers to the quantity of carbon dioxide emissions rather than literal weight.

Table 1 is a quick summary table comparing carbon credits, carbon offsets, regulated markets, and volunteer markets.

Table 1. Overview of Carbon Credits, Carbon Offset, and Carbon Markets

	Carbon Credit	Carbon Offset
Definition	Permits to emit a specified amount of CO_2; represents a ton of emissions.	Compensatory units generated by reducing emissions elsewhere.
Purpose	Used by companies and nations to meet emissions regulations	Used to voluntarily offset emissions, promote sustainability, or support green initiatives
Market and System	Regulated Market - Cap and Trade Program	Voluntary Carbon Market (VCM)
Operation	Companies with lower emissions can sell extra carbon credits to larger emitters	Who wants to reduce footprints can buy or invest in offset projects, such as reforestation or carbon capture
Regulatory Framework	Subject to regulatory requirements, often mandatory for some industries.	Voluntary, not legally mandated.
Issuers	National or international governmental organizations	Organizations that reduce carbon emissions
Project Supported	Typically focuses on reducing emissions within the entity's own operations	Supports external projects like reforestation, renewable energy, or carbon capture
Buyers	Mainly governments and companies required by law to participate.	Companies and individuals interested in reducing their carbon footprint.

b. Example of Regional Greenhouse Gas Initiative (RGGI)

The Regional Greenhouse Gas Initiative (RGGI) (RGGI, 2024a) is a collective effort among 11 northeastern states to reduce CO_2 emissions from power plants, combating climate change. Participating states (Figure 5), including Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont, are committed to lowering CO_2 emissions through this initiative.

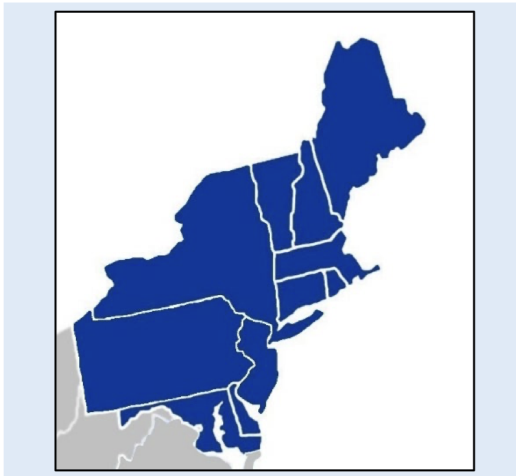


Figure 5. RGGI Participating States (RGGI, 2024a)

According to the RGGI official website (RGGI, 2024b), within RGGI states, certain power plants must acquire one RGGI CO_2 allowance for every short ton of CO_2 they emit. These allowances are distributed through quarterly auctions, creating a secondary market where they can be bought and sold. Each state issues allowances proportionate to its share of the regional cap, which decreases over time, leading to reduced emissions across the region. Proceeds from allowance sales are retained by the RGGI states, with each state determining how to best utilize them. Many states reinvest these funds into their communities, supporting clean energy programs, and energy efficiency initiatives, and providing bill assistance to local businesses and communities.

Maple forests have the potential to be part of offset projects under the RGGI program, particularly in the Forestry or Afforestation categories, which are eligible for CO_2 offset allowances. These offsets provide compliance flexibility and opportunities for low-cost emissions reductions and other benefits across sectors. The RGGI states have jointly developed regulatory requirements for offset categories, ensuring that awarded CO_2 offset allowances represent real, additional, verifiable, enforceable, and permanent emissions reductions or carbon sequestration, which some terms will be explained in more detail in the next section.

U.S. forest offset projects contribute to carbon sequestration through three main types: Reforestation, Improved Forest Management, and Avoided Conversion. Reforestation involves restoring tree cover on land with minimal or no existing tree cover, while Improved Forest Management activities aim to increase carbon stocks on forested land. Avoided Conversion actions prevent privately owned forestland from being converted to non-forest land use, often through conservation easements or public ownership transfers.

For additional tools and guidance documents, visit the RGGI website: https://www.rggi.org/allowance-tracking/offsets/offset-categories/forestry-afforestation.

c. Issue of Carbon Accounting and Offset Program

In the voluntary carbon offset market, where regulatory oversight is absent, environmental experts assume a pivotal role in evaluating and validating the legitimacy of carbon offset projects. These experts, typically employed by third-party certification organizations, conduct meticulous assessments to verify that projects effectively avoid, reduce, or remove greenhouse gas emissions. They scrutinize project methodologies, monitor emission reductions, and ensure compliance with established standards and best practices.

Below are summarized main challenges and requirements for third-party organizations to verify, as outlined by Kim and Pierce (2018): additionality, permanence, and leakage. We also mentioned earlier in the example of the RGGI carbon market.

Additionality refers to the necessity for a carbon offset project to bring about genuine reductions in greenhouse gas emissions that would not have occurred without the involvement of the offset buyer or buyers in the market. In essence, it questions whether the emissions reduction would have happened under a "business-as-usual" scenario. For example, if a carbon offset project motivates a maple syrup supplier to adopt sustainable tree management practices, it's crucial to ascertain if this change would have occurred independently. If the supplier already planned to implement these practices due to regulatory requirements or market demands, even without joining the offset program, they would still reduce emissions. Therefore, the offset program's incentives might not lead to additional emissions reductions.

Permanence underscores the importance of carbon sequestration lasting over a long period, typically decades or even centuries, for carbon offsets to effectively combat climate change. In the context of maple forests, permanence ensures that carbon sequestration by maple trees remains intact for the specified duration of the project. For instance, a maple forest conservation project aims to protect maple trees from deforestation, ensuring they continue to sequester carbon over the long term. By safeguarding maple forests from logging or land conversion, the project ensures sustained carbon sequestration, contributing to lasting reductions in greenhouse gas emissions.

Leakage means the unintended increase in greenhouse gas emissions or the shifting of emissions from one area to another due to carbon offset projects. It ensures that the emissions reductions achieved in one location do not simply relocate emissions elsewhere, resulting in no net decrease in carbon emissions. For instance, if a maple syrup producer's adoption of sustainable forestry practices leads to increased logging in neighboring forests, it constitutes leakage. Preventing such leakage is crucial for the effectiveness of carbon offset initiatives in the maple industry and ensuring genuine emissions reductions.

Other challenges include the costs of verification, the need for expertise in carbon accounting, and the allocation of resources, all of which can hinder entry into the carbon market. Additionally, once participating in the carbon market, maple forest owners sell the carbon credits generated from their trees, relinquishing ownership of the benefits of carbon sequestration as they have sold them. It is important to note that there are further limitations on land and forest management within some carbon markets.

For instance, in the case of RGGI, to ensure that CO_2 offset allowances awarded for U.S. forest projects represent permanent carbon sequestration, the RGGI States require a legally binding permanent conservation easement approved by the relevant state agency where the offset project is located. However, this requirement restricts the flexibility of land and forest management practices for participating landowners. Additionally, the conservation easement must expressly acknowledge that the Participating State is a third-party beneficiary, granting them the right to enforce all obligations under the easement.

SECTION 2. CLIMATE CHANGE & MAPLE SYRUP

I. Climate Change Impact on Maple Syrup Production

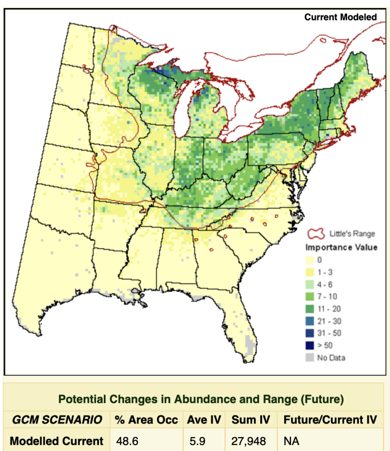
a. The Changing Range of Sugar Maple Habitats - Shifting Northward

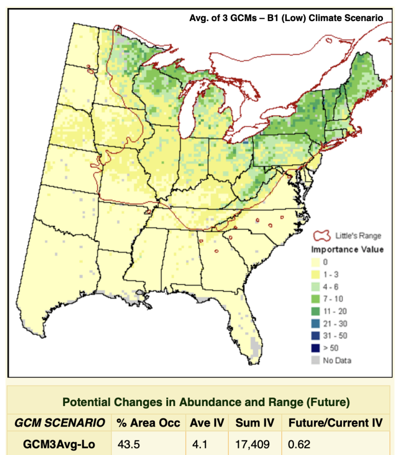
Climate change is expected to act as a catalyst for the northward migration of sugar maple habitats, driven primarily by the steady rise in temperatures and variations in soil characteristics. Projections derived from advanced computer models suggest that this transition will unfold gradually over the course of the next century. It is anticipated that regions in the southern and southwestern parts of the current range will witness a decline in suitable habitat, while areas farther north may become increasingly favorable for sugar maple growth (Giesting, 2023).

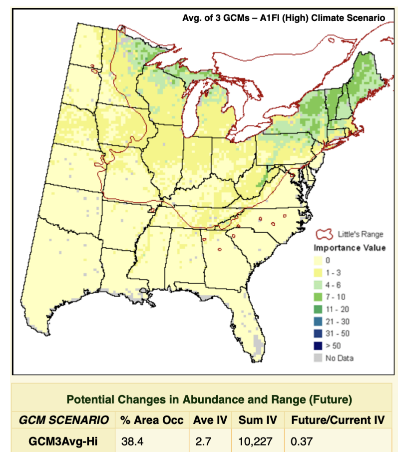
Despite these anticipated shifts, the sugar maple's remarkable longevity implies that immediate declines in population abundance are not guaranteed. Furthermore, geographical variations in risk factors present intriguing opportunities. For instance, regions such as the Great Lakes area may see the potential for increased sugar maple production, while northern locales like Maine, Ontario, and Quebec could experience higher sap yields (Giesting, 2023; Snyder et al., 2019).

Figure 6 below showcases data extracted from Version 4 of the Climate Change Atlas by the US Department of Agriculture Forest Service (USDA, n.d.). It illustrates the potential abundance and location changes of two common types of maple trees, sugar maple and red maple, under different climate change scenarios. The abundance change maps depict various scenarios comparing current conditions (1961-1990 baseline) with future projections (2071-2100) generated by three General Circulation Models (GCMs) and their averages. These scenarios are assessed under two emission scenarios: B1, representing a relatively high conservation emission scenario, and A1fi, indicating continued fossil fuel emissions.

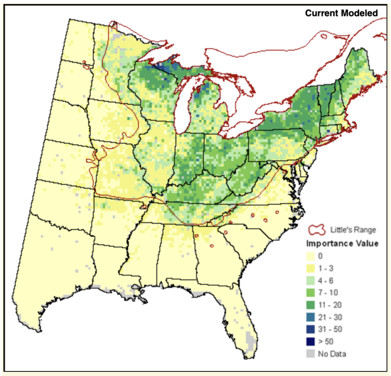
1961-1990 baseline	2071-2100 high conservation emission	2071-2100 continued fossil fuel emissions





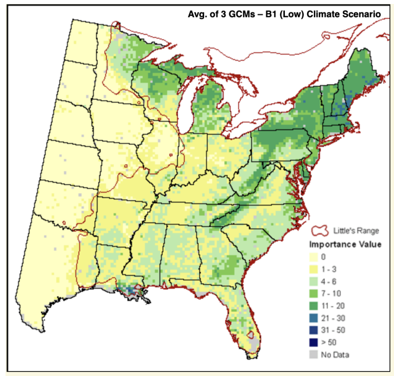


Sugar Maple (*Acer saccharum*)



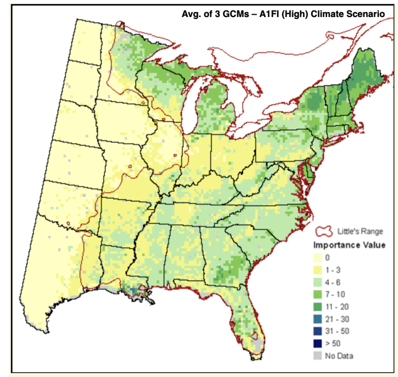
Potential Changes in Abundance and Range (Future)

GCM SCENARIO	% Area Occ	Ave IV	Sum IV	Future/Current IV
Modelled Current	48.6	5.9	27,948	NA



Potential Changes in Abundance and Range (Future)

GCM SCENARIO	% Area Occ	Ave IV	Sum IV	Future/Current IV
GCM3Avg-Lo	68	5.6	36,922	0.77



Potential Changes in Abundance and Range (Future)

GCM SCENARIO	% Area Occ	Ave IV	Sum IV	Future/Current IV
GCM3Avg-Hi	69.3	4.5	30,285	0.63

Red Maple (*Acer rubrum*)

Figure 6. Changes in Sugar Maple and Red Maple Distribution under Climate Scenarios (USDA Forest Service, n.d.)

b. Sugar Content Decline

The sugar content in maple sap is intricately linked to tree physiology, modulated by the delicate balance between photosynthesis and respiration (Rapp et al., 2019). During late summer and fall, maple trees halt active growth and begin storing excess starches in their sapwood. These starch reserves remain dormant until the wood temperature reaches around 40°F, prompting enzymes within the ray cells to convert the starches into sugars, primarily sucrose. However, warmer weather disrupts this process. As temperatures surpass approximately 45°F, the tree's respiration rate accelerates more rapidly than its photosynthesis rate, impacting carbon storage and ultimately diminishing sugar production. Despite the continuation of sap flow, the absence of functional enzymes leads to reduced sugar content in the sap, resulting in lower-quality syrup (Clark, n.d.).

Research indicates that for every 1°C increase in temperature from May through October, sap sugar content diminishes by 0.1°Brix. Historically, sap sugar content has maintained levels of 2°Brix or higher; however, under high emissions scenarios, projections suggest a decline of 0.55-0.65°Brix by the century's end. Consequently, future sugar content is anticipated to be lower and more variable (Rapp et al., 2019).

These changes bear significant consequences for maple syrup production. Producers are likely to encounter decreased yields owing to diminished sugar content, necessitating larger volumes of sap to produce equivalent syrup quantities. Modeling forecasts a decrease in sugar content across the sugar maple's range by 2100, with notable geographic disparities. Southern regions are expected to experience decreased yields, while northern areas may see increases. This forecasted shift in sap flow patterns, with the maximum sap flow region projected to move approximately 400 km northward by century's end, underscores the profound impact of climate change on maple syrup production (Rapp et al., 2019).

c. Sap Season Shift: Early Arrival Expected

Maple sap flow relies intricately on temperature fluctuations, necessitating cool nights below freezing (at or below 0°C / 32°F) followed by warm days to induce flow. This temperature-dependent process entails a cycle of freezing and thawing, with sap flow ceasing if temperatures remain consistently above or below freezing. The pressure differential within maple xylem tissue, driven by temperature fluctuations, propels sap exudation (Boyle, n.d.).

This process involves the movement of water through the xylem, the tree's vascular system responsible for transporting water and nutrients from the roots to the branches and leaves. Unlike in most trees where xylem cells contain water, maple trees have gas-filled cells. During freezing nights, sap-filled conduits expand, creating negative pressure, which pulls sap up from the roots. As the tree thaws during the day, gas-filled cells expand, generating positive pressure, pushing sap out. This cycle repeats for several days or weeks, with sap flowing into the tree at night and out during the day. Maple syrup producers often halt collection when trees start to bud because sap produced during this time can affect syrup flavor. When the freeze-thaw cycle ends, positive pressure within the tree ceases, and sap flow stops (Vermont Evaporator Company, 2020). Table 2 shows the rough timeline of maple syrup season.

Climate change is disrupting this delicate balance of temperature-dependent sap flow. Projections suggest that by the century's end, the maple sap collection season may start a month earlier than historical patterns, mainly due to shifting spring conditions and warmer winter temperatures, especially in southern maple regions where the freeze-thaw season begins earlier (Duchesne et al., 2009; Matthews and Iverson, 2017). Under high emissions scenarios, the midpoint of the sap collection season could occur a month earlier by century's end (Rapp et al., 2019).

The shifting start dates for the sugaring season pose challenges for producers, who may tap trees either too early or too late. Early tapping risks "drying out" trees, while late tapping results in missed sap runs (Cotnoir, 2021). With spring temperatures becoming more erratic, predicting sap flow initiation becomes increasingly difficult, exacerbating complications for maple producers.

Figure 7 illustrates that a rise in sapwood temperature above 32°F generates positive pressure within the tree, facilitating sap flow. With climate change causing warmer weather, the right picture depicts the early sap season onset. As climate change advances, the freeze-thaw cycle occurs earlier (Massachusetts Maple Producers Association, n.d.).

Figure 7. Early Onset of Freeze-Thaw Cycle Due to Rising Temperatures (Massachusetts Maple Producers Association, n.d.)

Table 2. Timeline of Maple Syrup Season (Massachusetts Maple Producers Association)

Summer	Chlorophyll in the leaves absorbs sunlight, while the roots absorb water and minerals from the soil. Photosynthesis converts simple sugar to starch, stored in the tree as an energy reserve and the basis for future sap.
Autumn	As temperatures drop, chlorophyll production slows, and the remaining sugar combines with other substances, leading to the vibrant colors of fall foliage.
Winter	Trees remain dormant, storing starch for conversion to sugar in spring, sweetening the sap for harvest.
Spring	The most active time for syrup production, as sugary sap rises to the top of the trees for harvesting.

d. Sap Season Shortening

As climate change disrupts traditional temperature patterns, the crucial freeze-thaw cycles necessary for sap flow are altered. With fewer fluctuations between freezing nights and thawing days, sap mobility is hindered, adversely affecting syrup production. The early onset of spring triggers premature bud break, leading to a shortened sap season and impeding production. Additionally, warmer temperatures promote the growth of microorganisms, resulting in premature clogging of tap holes and further hindering production (Duchesne and Houle, 2014; Giesting, 2023; Rapp et al., 2019).

e. Overall Reduction in Production

The combined effects of shortened and shifted sap seasons, along with a decrease in sugar content, are expected to diminish maple syrup production. Conservative projections indicate that by 2100, regions such as Virginia and Indiana may face challenges in producing any sap due to significant season shortening, while production in Québec is anticipated to rise notably. Conversely, many areas in the U.S. with sugar maples are projected to experience declines in maple production, while regions in northern Ontario and Québec may see moderate to substantial increases (Rapp et al., 2019).

Figure 8. is from Rapp et al. 2019 research, illustrating the shift in various maple syrup production indicators under the scenario for 2090-2099. It shows that the midpoint of the sap collection season, total sap amount, sap sugar content, and total syrup production all shift northward during this period. In the image, darker colors indicate higher values shifting upward, while lighter colors represent a decrease in value. This shift is evident across most of the continent, with colors becoming lighter.

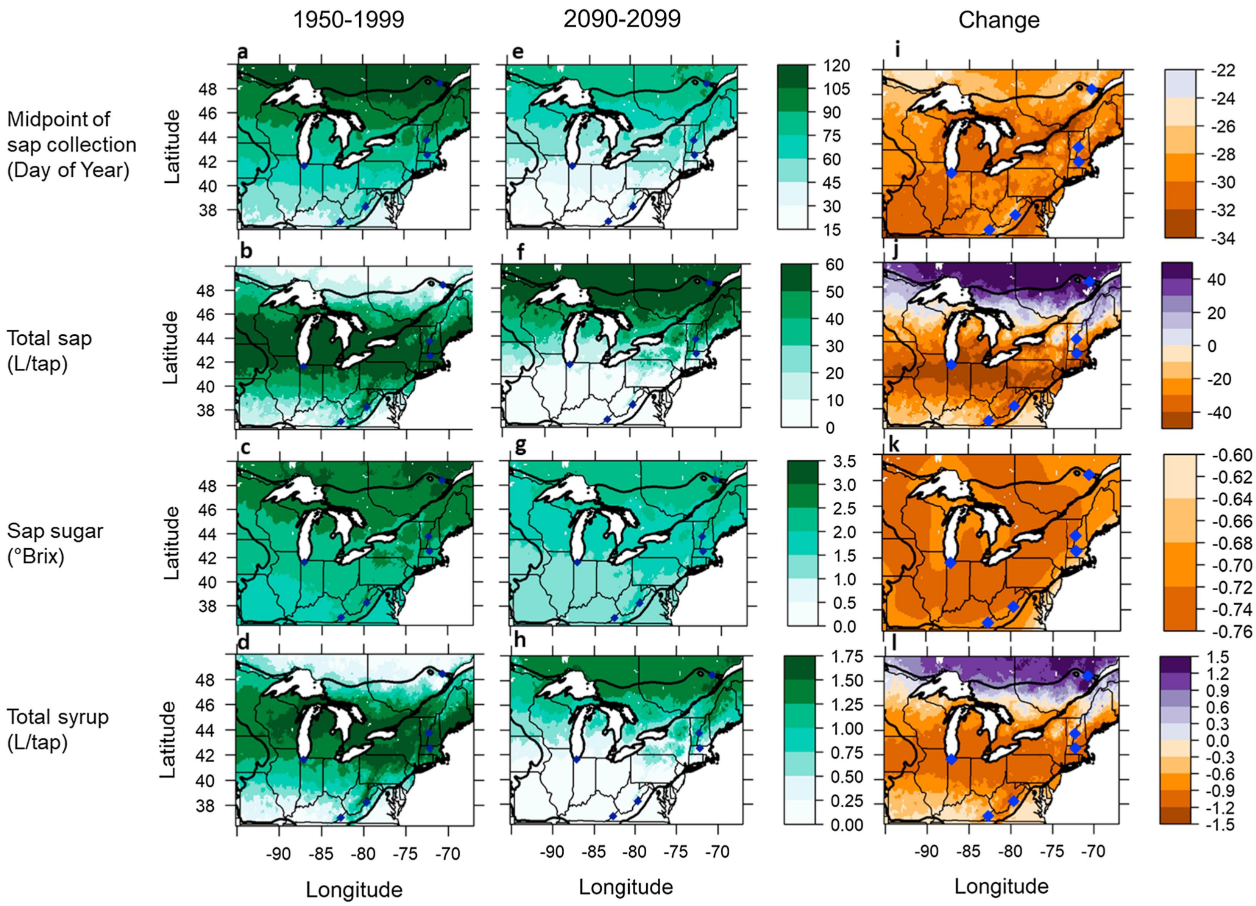


Figure 8. Northward Shift of Sap Collection Season and Syrup Production (Rapp et al., 2019)

f. Invasive Species Threaten Maple Trees

Invasive species pose a significant threat to trees, including the emerald ash borer, Dutch elm disease, and chestnut blight. With climate change, there's an increased risk of introducing new species or expanding the range of existing invasive ones (Maple from Canada, 2023). Moths, worms, beetles, and caterpillars are among the pests causing concern for maple syrup farmers as they damage the trees essential for syrup production (Maple from Canada, 2023).

For example, the Asian long-horned beetle (*Anoplophora glabripennis*) (ALB), originating from Asia, has been present in North America since the late 1990s. Recent studies indicate that ALB may extend its range due to warmer temperatures. The ALB primarily targets maple but also feeds on other hardwoods such as birch, elm, ash, poplar, horse chestnut, and willow (Slele Prism, n.d.).

Another invasive species to watch out for is the spotted lanternfly (*Lycorma delicatula*)(SLF), native to Asia. SLF feeds on over 100 plant species, including sugar maples, with a preference for silver and red maples (Slele Prism, n.d.).

Invasive plants and animals further disrupt the region's forests. These invaders establish themselves, creating low shade that inhibits maple seedlings' growth. Invasive earthworms also disturb the forest floor by consuming the organic humus layer, hindering maple establishment (Gula, 2023).

Forest tent caterpillars pose yet another threat to sugar maple health. Outbreaks of these caterpillars result in defoliation, diminishing the trees' ability to photosynthesize and grow. Repeated outbreaks over several years can severely damage tree health (Gula, 2023).

Figure 9. Asian Long-horned Beetle (National Invasive Species Information Center, n.d.-a)

Figure 10. Spotted Lanternfly (National Invasive Species Information Center, n.d.-b)

g. Extreme Weather

Climate change brings about an escalation in severe weather events that significantly affect the health of maple trees. These events encompass storms, floods, droughts, acid rain, invasive species, and soil degradation (Maple from Canada, 2023).

Wind and ice storms pose threats by uprooting maple trees, while droughts can prove fatal to seedlings and impede root growth. Diminished snow cover, which typically provides moisture and insulation to roots against the cold, exposed roots, making them susceptible to freezing (Maple from Canada, 2023).

With the likelihood of decreased snowpack in regions where it was once prevalent due to warmer winter temperatures, the soil becomes more prone to freezing, amplifying mortality rates and turnover in fine roots (Giesting, 2023; Reinmann et al., 2019; Tierney et al., 2001). Increased soil frost depth and duration have shown adverse effects on aboveground growth in sugar maples, potentially undermining carbon storage in forests (Giesting, 2023; Maguire et al., 2017). One study revealed a 40% decline in aboveground growth attributable to increased soil freezing, resulting in an estimated 8.8% reduction in forest carbon storage among forests accustomed to snowpack conditions (Giesting, 2023).

II. Management Strategies

a. Increased Sap Collection Methods to Boost Production

Implementing innovative sap collection methods can significantly enhance maple syrup production, especially in the face of climate change challenges. Adopting additional taps and leveraging advancements in technology and infrastructure, such as plastic tubing and vacuum systems, offer promising avenues for maximizing sap yields (Duchesne and Houle, 2014; Giesting, 2023; Matthews and Iverson, 2017; Rapp et al., 2019).

Transitioning to tubing systems for sap collection presents several advantages over traditional bucket and bag methods. Tubing systems offer enhanced sanitation, allowing for earlier tapping without compromising late-season sap yields (Maple Syrup Program, n.d.). Maintaining cleanliness by regularly cleaning tubing and using new, sterile spouts each year is crucial for optimizing sap production (Helmer, 2018).

Moreover, employing vacuum systems, particularly when temperatures rise above freezing during the syrup season, can further improve sap extraction efficiency (Maple Syrup Program, n.d.). By utilizing pressure to extract sap from trees, vacuum systems mitigate reliance on gravity, thereby enhancing overall collection rates (Helmer, 2018).

b. Protecting Against Invasive Species

Protecting maple trees from invasive species is essential for maintaining healthy forests and sustaining maple syrup production. It involves educating oneself about identifying and managing invasive species prevalent in the area, utilizing resources from the National Invasive Species Information Center and state-specific sources. Effective strategies for managing or removing common invasive plants like buckthorn and garlic mustard should be learned, as they can hinder maple regeneration and compete with native vegetation. Practicing cleanliness by cleaning boots, gear, and vehicle undercarriages before moving between woodlands helps prevent the inadvertent spread of invasive species and their eggs (Maple Syrup Program, n.d.).

Encounters with invasive species in woodlands should be documented and promptly reported to local Extension agents or state foresters. Regular monitoring of woodland health is also crucial, as healthy trees are better equipped to withstand insect infestations and disease outbreaks. Additionally, exploring support programs offered by states or the USDA Natural Resources Conservation Service can provide assistance for managing invasive species effectively (Maple Syrup Program, n.d.).

c. Alternative Tree Species - Red Maple

In response to changing climate conditions, considering alternative tree species such as red maple (*Acer rubrum*) for syrup production presents a viable adaptation strategy. While sugar maple remains the preferred species for syrup production, red maple offers several advantages and considerations (Maple Syrup Program, n.d.).

Although red maple sap typically contains lower sugar content, requiring more boiling time to achieve syrup consistency, it still produces high-quality syrup. Moreover, red maple demonstrates greater adaptability to diverse soil conditions compared to sugar maple, potentially enhancing its resilience amid changing climate conditions (Cotnoir, 2021).

Despite co-occurring in many areas, sugar and red maple exhibit differences in habitat preferences. Sugar maple thrives in nutrient-rich environments with calcium-rich soils, while red maple shows adaptability to diverse environments, from dry acidic sites to wetlands. Sugar maple is renowned for its shade-tolerance, thriving under dense canopies with minimal sunlight exposure, while red maple exhibits moderate shade tolerance. In terms of growth characteristics, sugar maple boasts a longer lifespan, averaging around 200 years, compared to red maple's average lifespan of 80-100 years (Tapper, 2019).

From a commercial perspective, sugar maple is valued for its dense, hard wood, often used for high-end applications such as veneer production. In contrast, red maple, known for its softer wood, finds applications in flooring and furniture-making. Both species yield high-quality firewood and serve as sources for maple syrup production, with sugar maple historically dominating syrup production. However, red maple's increasing utilization in syrup production signifies its rising significance in the maple industry (Tapper, 2019). Table 3. shows a quick summary for the difference between Sugar Maple and Red Maple.

Table 3. Contrasting Sugar Maple and Red Maple Characteristics

	Sugar Maple (*Acer saccharum*)	Red Maple (*Acer rubrum*)
Shade Tolerance	High	Moderate
Soil Preference	Nutrient-rich	Versatile across various soil types
Lifespan	Around 200 years	80-100 years
Habitat Preference	Rich-site environments	Diverse environments
Wood Characteristics	Dense, hard wood	Soft wood
Commercial Applications	Veneer production	Flooring, furniture-making
Syrup Production	Higher sugar content	Lower sugar content
Manufacturing	Less boiling time	More boiling time

d. Optimizing Maple Tree Health and Productivity through Silvicultural Practices

Silvicultural practices are instrumental in promoting the health and productivity of maple trees. Trees with expansive crowns and minimal competition tend to yield higher quantities of sweeter sap (Duchesne & Houle, 2014; Giesting, 2023). Before initiating thinning operations, assessing the sugar content of individual trees is prudent, as sweetness appears to be a consistent individual characteristic over time (Wilmot & Brett, 1995; Giesting, 2023).

Firstly, monitoring crown health is crucial, as unhealthy crowns can lead to reduced sugar production and lower yields in subsequent sap seasons. Symptoms such as dead branches in the upper part of the crown, poor leaf color, or unusually small leaves may indicate poor crown health and underlying issues such as root problems or repeated injury to the crown (Hammonds, 2017).

Assessing competition for light among trees is another vital aspect of silviculture (Hammonds, 2017). Sugar maple requires adequate light for optimal growth, and excessive competition can hinder its development. Visual cues, such as a closed upper canopy or lack of seedling growth, may indicate excessive shade or competition. Thinning around the best trees can alleviate competition and ensure sufficient light for maple trees to thrive (Hammonds, 2017).

Monitoring tree diameter growth is also critical for maple syrup producers, as it is indicative of crown health and sap production potential (Hammonds, 2017). Annual measurements of tree diameter growth provide insights into tree vigor and future tapping potential. Producers should expect specific annual diameter increments based on tree size, with measurements taken consistently at breast height using standardized methods (Hammonds, 2017).

Considering tree age and longevity is also essential in silvicultural management. While sugar maple can be long-lived, reduced production is expected between 150 and 250 years of age (Hammonds, 2017). Regenerating patches of old or unproductive maples every few years can help maintain productivity, with careful consideration given to protecting young seedlings from deer browsing. Removing dead or dying trees that encroach upon tapping trees can also promote vigorous growth, although standing dead trees provide valuable wildlife habitat (Hammonds, 2017). Below table 4. shows a summary of all silvicultural practices.

To mitigate the risk of floods and erosion, adherence to best management practices during construction and maintenance activities within the sugarbush is crucial (Maple Syrup Program, n.d.). It is also essential to learn how to manage flood damage to trees effectively. Table 4 shows the overall summary of silvicultural practice.

Table 4. Summary of Silvicultural Practices for Maple Trees

Practice	Key Considerations
Crown Health Monitoring	Check for dead branches, poor leaf color, or small leaves
Competition Assessment	Look for a closed upper canopy or lack of seedling growth
Tree Diameter Monitoring	Measure annual diameter growth at breast height
Tree Age and Longevity	Regenerate patches of old or unproductive maples every few years
Flood and Erosion Control	Adhere to best management practices during construction

e. Enhancing Maple Tree Health through Tree Species Diversification

A diverse mix of trees, including large, medium, and small ones of varied ages and economic value, contributes to the vitality of the forest ecosystem. Such diversity not only enhances carbon storage and soil regeneration but also provides essential habitats for birds and other species, fostering overall ecosystem health.

Mixing tree species is crucial for maintaining forest resilience against various stresses, such as insect infestations. While prioritizing healthy maples is common, cutting less productive or risky maples can be necessary. When cutting firewood or thinning, aiming for a canopy composition of approximately 75% sugar maple or red maple and 25% other species is advisable, serving as a flexible guideline rather than strict rules (Hammonds, 2017).

f. Soil Health - Improving Composition for Maple Trees

Sugar maples thrive in rich, moist soils, but invasive earthworms disrupt forest ecosystems by altering soil composition, depleting vital nutrients, and exacerbating soil dryness and runoff (Bal, et al., 2018). Acid rain further compounds the issue, increasing soil acidity and depriving sugar maples of essential calcium, leading to weakened canopy vigor and tree mortality (Moore, 2020). Table 5 indicates the soil factors suitable for maple trees.

To mitigate these impacts and enhance soil health for maple trees, several strategies can be implemented:

1. Lime and Fertilizer Application: If the soil is acidic or lacking in nutrients, consider applying lime or fertilizer to replenish essential elements. Lime application can be done manually, with mechanical spreaders, or aerially. Specialized wheeled mechanical spreaders designed for sugarbushes offer efficient application methods (Maple Syrup Program, n.d.).
2. Preventing Soil Ruts and Compaction: Protecting tree roots from damage is crucial for tree health. Avoiding soil ruts and compaction caused by heavy machinery, such as tractors and skidders, is essential. Limiting the number of trails, especially in damp areas, and employing techniques like installing corduroy in wet zones can minimize soil damage (Hammonds, 2017).

Table 5. Factors to Consider for Soil Health (Blain's Farm & Fleet, 2015):

	Description
Soil Type	Maple trees thrive in moist, well-drained soils with a fine to medium texture. Avoid planting in dry, sandy, or rocky soil types to ensure optimal growth conditions.
Soil Moisture	Adequate soil moisture is vital for maple trees, especially in shaded, damp areas. Regular watering may be necessary to maintain soil moisture levels.
Soil pH	Soil acidity profoundly influences maple tree growth, with sugar maples preferring slightly acidic to neutral soils (pH 6 - 7.5). Adjusting soil pH can optimize soil health.
Soil Fertilizer	While maple trees typically do not require fertilizer, using tree-specific fertilizers or mycorrhizal treatments can enhance growth and soil health.

By addressing soil composition and implementing soil management practices, maple producers can enhance soil health, promote tree vitality, and mitigate the adverse effects of environmental stressors on maple tree growth and productivity.

III. Conclusion of Mitigation Plan Under Climate Change

Climate change has significantly impacted maple forests, resulting in a reduction in maple syrup production. It is crucial to focus on increasing forest productivity to mitigate these effects. While the management plan described above may lack innovation, as many maple syrup suppliers have already implemented similar strategies, it is imperative to emphasize the need to pay increased attention to these management practices now to recover from production losses effectively.

In addition to routine practices like increasing sap collection and employing tubing and vacuum systems, larger-scale silvicultural plans such as thinning or diversifying maple forest structure with different maple species are crucial. Seeking guidance from professionals and experts, such as the local USDA Natural Resources Conservation Service office, can aid in further strategic planning. For additional information and assistance, please visit the USDA NRCS website at: https://www.nrcs.usda.gov/contact/find-a-service-center

CHAPTER 2

SECTION 1. MODELING DOWNSTREAM DISTRIBUTION FOR THE MAPLE SUPPLY CHAIN

One major challenge of modeling the life cycle impacts of maple products was low industry visibility into a complex downstream supply chain. The Center for Sustainable Systems' LCA is based on primary data collection from voluntary participants, providing information about their production operations over the course of the maple syrup season. This cohort of producer participants has the insight to provide detailed information on their operations, enabling access to high resolution data for the extraction and manufacturing phase of the maple syrup life cycle. For the average maple producer, operations begin at the tap and end when maple syrup or sap is delivered to a packer-distributor or point-of-sale, such as a retailer or farm stand.

Producers also likely have some visibility into their upstream supply chain. While they may not have unique insight into the operations of their suppliers, they typically have access to information about which vendors supply their equipment and materials. They are also able to provide data on their emissions sources from energy, whether they be Scope 1 (i.e., diesel generators or wood-fired evaporators) or Scope 2 (electricity sourced from the regional power grid).

Where the maple supply chain becomes more opaque and difficult to evaluate is in downstream distribution for the larger domestic and global maple syrup market. While thousands of independent producers in the US produced nearly 4 million gallons of maple syrup in 2021, only 24% of this syrup was sold by the producers as a retail or wholesale product (NASS 2024). This 24% includes retail syrup that is sold direct-to-consumers (at the sugarbush, farmstand, or online), as well as wholesale syrup that is sold business-to-business from the producer (to restaurants, food & beverage companies, or retail partners like supermarkets).

The other 76% of maple syrup is sold in bulk to large packer-distributors that source syrup from hundreds or thousands of producers, bottle and label it, and sell it under various brand names to retailers all over the world (M. Rechlin, personal communication, May 17, 2023). Once the syrup arrives in drums to these facilities it is graded and offloaded into large tanks, where it mixes with bulk syrup from maple-producing regions across North America.

In order to maintain contracts with major retail chains like Kroger's, Whole Foods, and Trader Joe's these packer-distributors must guarantee sales volumes for an agricultural product characterized by unpredictable regional and seasonal variability. Large packer-distributors source syrup from both the US and Canada to meet this demand. In seasons where northeast production is low, packers will purchase bulk syrup from as far away as Michigan (C. Anderson, personal communication, July 18, 2023). Like other disaggregated agricultural supply chains, such as palm oil or cocoa, maple syrup lacks traceability once it arrives at the packing plant. Furthermore, information on sales data and business partnerships for packer-distributors is proprietary, and therefore not available to the industry at large. These difficulties around data accessibility and supply chain transparency presented significant barriers to modeling the downstream impacts of maple syrup in a cradle-to-grave LCA.

Thus, our analysis supplemented the CSS model by picking up where the primary data collection would end – at the sugarbush gate, where producers largely lose supply chain visibility and primary data collection offers little insight. To adequately assess the transportation footprint of maple syrup in the United States it was essential to quantify the weight of the syrup being distributed annually, the weight of the packaging required to transport this quantity of syrup, and the distance that syrup is traveling in the US. This model of downstream distribution therefore comprised three sub-components:

1. Estimating regional consumption of maple syrup across the US.
2. Estimating the weight of maple products distributed across the US, including syrup and packaging.
3. Estimating the distance that maple syrup travels from tree to customer.

For the purposes of this analysis, only syrup transported to and distributed within the US for domestic consumption was considered. Global exports of syrup produced in the US fell outside the scope of this model. Further, only states that produce syrup and participate in the NASS survey have freight transport associated with retail and wholesale syrup in this model.

The total freight transport associated with syrup traveling to each state was calculated in tonne-kilometers as:

$$\text{Total Tonne} - \text{Kilometers of Maple Freight Transport (tkm)} = \begin{array}{c} \text{Mass of Bulk Syrup from Producer to Packer (tonnes)} \\ \times \text{ Distance from Producer to Packer (km)} \\ + \\ \text{Mass of Bulk Syrup from Packer to Retailer (tonnes)} \\ \times \text{ Distance from Packer to Ratiler (km)} \\ + \\ \text{Mass of Retail \& Wholesale Syrup from Producer to Retailer (tonnes)} \\ \times \text{ Distance from Producer to Retailer (km)} \end{array}$$

This model, devised for calculating tonne-kilometers associated with maple syrup distribution throughout the US, was ultimately used by CSS researchers to assess the distribution impacts of syrup within their LCA framework. The scope, assumptions, and process of this analysis are detailed in the following sections.

I. Scope of Analysis

a. In Scope

Transportation associated with: 1. Bulk maple syrup distributed domestically within the US; 2. Bulk maple syrup imported from Canada and distributed domestically within the US; 3. Retail and wholesale maple syrup sold on-site at the sugarbush or locally via retailers or farm stands.

b. Out of Scope

Transportation associated with: 1. Bulk maple syrup produced in the US and exported globally; 2. Retail and wholesale maple syrup sold via e-commerce and distributed with third-party shipping services; 3. Bulk and wholesale maple syrup sold to food and beverage companies as an input into other products; 4. Sap processed on offsite boiling facilities, or with third party boiling facilities; 5. Syrup products traveling from third-party retailer warehouses to third-party retail outlets.

Data from the US Department of Commerce International Trade Administration (ITA, 2023) indicates that maple syrup exports from US States were collectively valued at $29.5 million in 2022, or 13.6% of the total US-produced syrup market. However, it is worth noting that these exports include syrup not produced in the US. Syrup imported from Canada and subsequently exported abroad would appear in this data as a US export. Further, a Technavio market report of the global maple syrup market found that online sales of syrup comprised 9.8% of the total syrup market in 2020 (Technavio, 2020). Given that export data would be inclusive of online sales to customers outside the US, we assume that 10-20% of US-produced syrup is distributed through international and e-commerce channels. This segment of the market was nevertheless excluded from the model due to lack of traceability for syrup that travels through global and e-commerce supply chains. The model put forth here accounts for the 80-90% of maple syrup that is domestically shipped and purchased via physical points-of-sale.

II. Model Assumptions

This model relied on a number of assumptions, details below:

- Bulk syrup is consumed at the same average per capita rate across the US. State population is the sole determinant for bulk syrup distribution in the US.
- Retail and Wholesale maple syrup distribution occurs in the same State where the syrup is produced.
- Bulk syrup from the US and Canada is primarily purchased by 3 major US packer-distributors that make up over 80% of the maple syrup market, and the syrup from these packers is distributed nationally.
- Syrup exports are part of bulk syrup sales, not retail or wholesale syrup sales.
- Conversion of sap to syrup occurs on-site at the sugarbush.
- Syrup shipped from the packer-distributor is transported directly to a point-of-sale, rather than the warehouse of a third-party retailer.
- All packaging is assumed to be at carrying capacity when traveling.
    - Ex. Every 55-gallon syrup drum contains 55 gallons of syrup, every pallet carries a standard number of cases, every truck is full, etc.
- Bulk syrup in Maine, New Hampshire, Vermont, and New York is sent to packer-distributors in the Northeast. Bulk syrup in Michigan and Wisconsin is sent to distributors in the Midwest. Bulk syrup in Pennsylvania is sent to the packing hub closest to the sugarbush.

It is worth noting that some of these assumptions are made for the feasibility of modeling, and may not in fact represent the actual supply chain.

III. The US Maple Syrup Distribution System

As discussed above, retail and wholesale syrup follow a different distribution pathway than bulk maple syrup. Retail maple syrup is typically sold either at the sugarbush directly to consumers, or via local farm stands and markets in close proximity to the sugarbush. Bottling largely occurs on-site at the sugarbush. There are no standardized transportation logistics. Producers may deliver syrup to shops and farm stands with crates and packaging materials that get reused repeatedly, or they may use single use packaging on a case-by-case basis. For the purposes of this model, only bottle weight is considered in retail and wholesale transit since additional packaging methods vary so widely. Additional packaging materials are considered for bulk syrup, as bulk distribution channels adhere to more consistent industry standards around shipping and packaging material requirements.

Bulk syrup is sold to packer-distributors from syrup producers in barrels. A standard steel barrel ranges from 30 to 55 gallons (Bascom Maple, n.d.-a). These barrels are returned to producers after the syrup is transferred into large storage tanks at the packer-distributor facility. The syrup is then bottled into glass and plastic containers of varying sizes, labeled, and boxed. These maple syrup products are then loaded onto standard wood pallets and secured with plastic stretch wrap or pallet bands, depending on the product being transported. Pallets are then delivered to customers via trucks, where they are unloaded. Pallets and shipping materials are not returned to the packer-distributor, as is industry standard. Consumers then purchase syrup at retail locations across the country (C. Anderson, personal communication, July 18, 2023).

a. Estimating Regional Consumption of Maple Syrup Across the United States

To assess the tonnes of syrup transported annually to different parts of the US, this project had to model maple syrup supply across the country. Point-of-sale scanner data on platforms like Circana and Nielsen IQ provide the most detailed data on regional market size for packaged goods, however these expensive databases were not accessible to us for this project. As a proxy for regional sales, we modeled consumption as an indicator of regional demand – and ultimately, regional supply. This model calculated average per capita US syrup consumption using the equation:

$$Average\ US\ Maple\ Syrup\ Consumption\ Per\ Capita\ \left(\frac{Gallons}{Person}\right) =$$

$$\frac{US\ Domestic\ Bulk\ Syrup\ Production\ \left(\frac{Gallons}{Year}\right) + Canadian\ Syrup\ Imports\ \left(\frac{Gallons}{Year}\right) - International\ Syrup\ Exports\left(\frac{Gallons}{Year}\right)}{US\ Population}$$

The data used in this model come from the 2020-2021 USDA NASS Maple Syrup Report (NASS, 2023), UN Comtrade (UN Comtrade Database, n.d.), and US Census Bureau datasets (United States Census Bureau, 2023). Imports and exports were converted from monetary (*USD*) to physical flows (*gallons*) using average dollar per gallon bulk syrup pricing for the corresponding years and Canadian to US dollar exchange rates (IRS, 2024). Estimates of bulk syrup distribution were then allocated to each state using the equation:

$$State\ Syup\ Consumption\ (Gallons) = Average\ Per\ Capita\ Consumption\ \left(\frac{Gallons}{Person}\right) \times State\ Population$$

One weakness of this approach is that it does not account for regional tastes and consumption patterns across the US. This low-resolution estimate assumes that every American consumes the same amount of syrup originating from bulk sales, annually. The only driver for bulk syrup distribution is the state population. However, from speaking with industry professionals we know this not to be the case. The preference for maple syrup over corn syrup-based table syrup like Log Cabin is, at least in part, regionally determined. Anecdotal evidence indicated that maple syrup is consumed at higher rates in areas where maple syrup is produced. In producing regions, maple syrup is often integrated into local cuisine and culture, and per capita syrup consumption is therefore likely higher in New Hampshire than New Mexico.

To account for some of this variation, the consumption model allocated retail and wholesale syrup separately from bulk syrup. Syrup sold directly from producers via retail or wholesale operations was allocated to the state in which the syrup was produced. Interviews with industry experts confirmed that retail and wholesale business largely occurs in local markets. Typically, less than 10% of such business occurs via online retail platforms that sell syrup nationally or internationally on a per-order basis (Technavio, 2020). Lastly, syrup quantities were converted from volume to weight using the industry standard conversion factor: 1 gallon of maple syrup = 11 lbs of maple syrup. All units of weight were ultimately converted to *tonnes*. Figure 11 shows the states with the highest total syrup consumption volumes in 2021, based on this model.

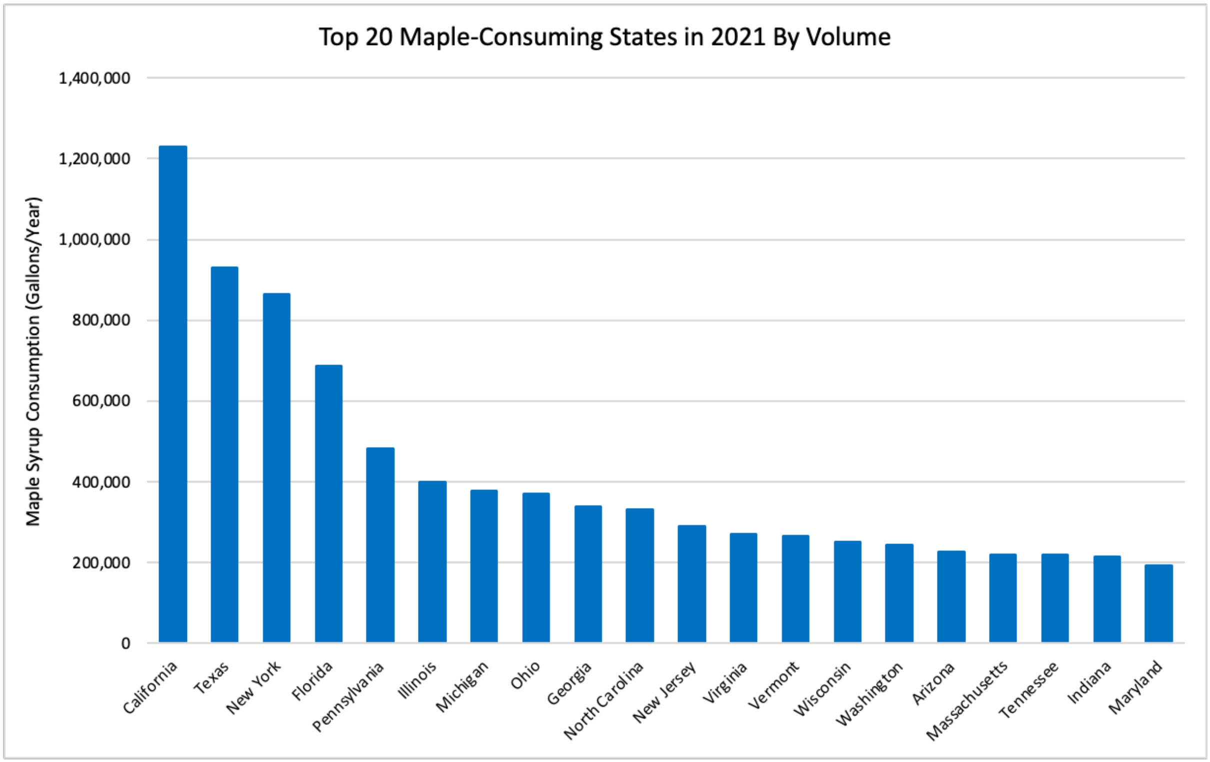


Figure 11. Quantity of syrup consumed in the 20 highest syrup-consuming US States in 2022.

Based on this model the states with the largest populations like California, New York, and Texas still rank as the top three consumers of syrup. To meet demand levels, 1.2 million gallons of syrup would be transported to California in 2021 based on our model output. Further, allocating retail syrup sales to the producer states meant that Vermont, which has the second lowest population in the United States, was the 13th highest syrup-consuming state. All seven states surveyed for the USDA National Agricultural Statistics Survey were represented in the top 30 highest syrup consuming states, despite these states having some of the smallest state populations in the US. These results indicated that our model was a reasonable representation of the syrup consumption landscape. We consulted two different industry professionals with a combined 33 years of maple syrup industry experience to confirm the validity of this approach and the resulting outputs.

b. Estimating the Weight of Maple Products Distributed Across the US: Syrup and Packaging Inclusive

The second component of the model was estimating total packaging weights for different shipment scenarios. Since it was difficult to segment the syrup market by container size without scanner data or access to proprietary sales data from a cooperating packer-distributor, we instead built a dynamic model that allows the user to assess different packaging scenarios. In this model, the thirteen most common packaging types listed in Table 6 were considered.

Table 6: Maple Syrup Packaging Types

Epoxy Steel Drum	30 Gallon
	55 Gallon
Stainless Steel Drum	30 Gallon
	40 Gallon
	55 Gallon
Glass Bottle	8 Ounce
	12 Ounce
	16 Ounce
Plastic Jug	8 Ounce
	16 Ounce
	32 Ounce
	64 Ounce
	128 Ounce (= 1 Gallon)

In addition to the container, maple syrup transportation also requires packaging for shipping, which includes:

- Corrugated cardboard boxes
- Corrugated cardboard dividers for glass bottle shipping
- 40” x 48” pine wood pallets
- LDPE stretch wrap for securing boxes onto pallets
- ½” poly strapping for securing barrels onto pallets

The tare weights for packaging came from a variety of Maple Supply Catalogs (Bascom Map, n.d.-b). Specs on the size of box configurations, box sizes, pallet configuration, and protective shipping materials came from industry sources at two leading packer-distributors, one in the Midwest and one in the Northeast.

The total weight of the packaging required to transport all the syrup headed for a certain destination was then calculated as:

$$Total\,Weight\;of\;Packaging\;Materials\;(tonnes) = \frac{Syrup\;Volume\;(Gallons)}{Packaging\;\;Size\;(Gallons)} \times Weight\;of\;Materials\;Required\;to\;Ship\;(tonnes)$$

Once bottle or barrel types are selected, the model is populated with the weight of all packaging materials required to transport the entire quantity of syrup to the State selected.

c. Estimating the Distance that Maple Syrup Travels from Tree to Customer

The third component of this model was estimating the transportation distances that syrup would travel to move along each node of the supply chain.

Transportation distances were calculated in 3 phases:

1. Retail or wholesale producer to local retailer
2. Bulk seller to packer-distributor
3. Packer-distributor to national retailers in every state

The assumed distance from retail or wholesale seller to local retailers was based on the average distance between rural homes in the US and the nearest food retailer (Rhone and Ploeg, 2019). Since many sugarbushes also function as rural residences, this model applied a 5km average distance to all scenarios of retail and wholesale syrup distribution.

Modeling the distance from bulk sellers to packer-distributors required a different approach. We first conducted a market landscape analysis of the maple syrup industry using annual revenue reporting to determine which packer-distributor hubs had the greatest market share and were therefore likely to be the largest aggregators of bulk syrup (D&B Hoovers, n.d.). This analysis revealed that three major US packer-distributors - Bascom Maple Farms Inc, Maple Grove Farms of Vermont Inc., and Butternut Mountain Farms Inc. - make up over 80% of the US packaged syrup market. These companies each have a single large processing facility located at or near their company headquarters. The three facilities are headquartered within 200 km of each other in Vermont and New Hampshire, geographically positioned as a triangle. Strafford, Vermont was identified as a town located in the center of this triangle, near equidistant from all three. From this point forward, Strafford VT was used as a focal point for Northeast maple packaging.

The NASS QuickStats database (NASS, n.d.) was used to assess average distance between Northeast producers and Strafford, Vermont. All counties in Maine, New Hampshire, New York, Pennsylvania, and Vermont with more than 10 listed maple producers were considered in this analysis. These counties were mapped and color coded based on relative concentration of registered sugarbush operations, as shown in Figure 12. Michigan, Wisconsin, Minnesota and Ohio were excluded from sugarbush-to-packer distance calculation. We assumed that bulk syrup in the Midwest is largely sold to Midwest packer-distributors and is not transported all the way to the Northeast for bottling, so including these producers in an analysis centered around Strafford, VT would introduce error. Distance from producers to Strafford, Vermont was calculated using a weighted average to account for the varying number of producers in different counties to settle on a reasonable transport distance for this phase of the model.

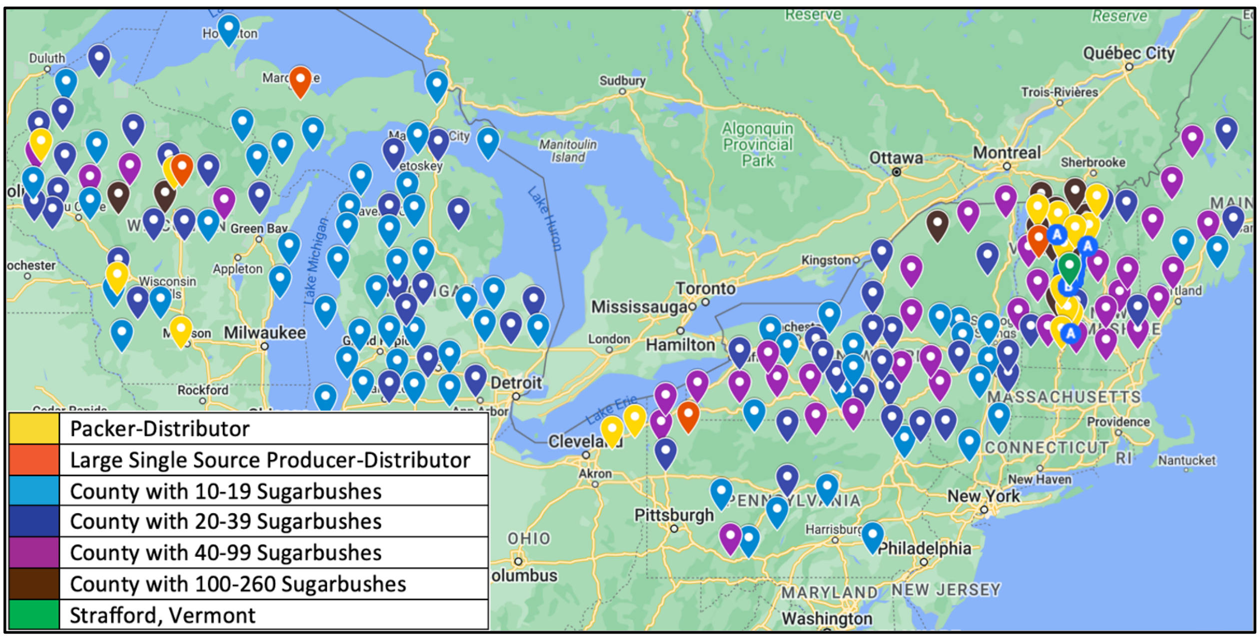


Figure 12. Map of sugarbushes and packer-distributors in US States (NASS Quick Stats Database) surveyed in the 2022 NASS Maple Syrup Crop Production Report

The model also assumed that all syrup coming from Canada travels the average distance from Quebec City to Strafford. Quebec City was selected as a geographic reference point in Quebec, since this province produces 90% of Canadian maple syrup (StatCan, 2022). A final weighted average that considers the relative amount of syrup coming from the Northeast and Canada was used to calculate average distance between seller and packer-distributor in this model. The average sugarbush to packer-distributor distances used in this model were as followed:

Table 7. Average sugarbush to packer-distributor distances

	Miles	Kilometers
Domestic US Sugarbush to Packer-Distributor	201	323
Canadian Sugarbush to Packer-Distributor	283	455

For the last leg of the journey, this model assumed that the average distance from packer-distributor to nation-wide retailers was equal to the distance between Strafford, VT and the most populous city in each US State.

IV. Utilizing this Model for an In-Depth Maple Packaging Analysis

Modeling the downstream distribution of maple syrup was a critical component of the CSS Maple LCA. This model was ultimately integrated into the comprehensive cradle-to-grave LCA conducted by the CSS, to measure transportation-related emissions impacts in the syrup supply chain. The analysis underscored the critical importance of quantifying downstream distribution metrics for a consumer packaged good like maple syrup, which is manufactured regionally and transported across the US. Based on our model, if all maple syrup consumed in the United States was sold as 12 oz glass syrup bottles, the distribution of maple products would have required 227 million tonne-kilometers of transport in 2021. If freighted in an average US diesel powered long-haul truck, this combined transportation would have released 22 million kg of CO_2e that year (Argonne GREET Model, n.d.), around the same annual carbon footprint of 5,000 US passenger cars (US EPA, 2023a).

This distribution model also proved invaluable as a key research question emerged around optimal packaging choices for syrup distribution. In the course of our research, we had the opportunity to engage with a leader at a major US packer-distributor with expert knowledge of the maple industry landscape. While this industry professional had deep insight into the US maple syrup supply chain and market dynamics, one key information gap they identified was the lack of understanding or consensus around the systems impacts of different container choices for syrup. This industry veteran had worked with hundreds of retailers all over the country to pack and deliver maple syrup, and they noted a distinct preference for glass bottling from some retail customers who claimed to prioritize sustainability in their sourcing decisions.

They expressed that glass packaging was often perceived as a more sustainable alternative to plastic due to its high recycling rates and reusability, however their intuition told them this was unlikely to be the case. They hypothesized that glass packaging may have an outsized impact due to the weight of bottles and the global structure of the supply chain when compared to the relatively light and regionally produced plastic jugs used by most Northeast packer-distributors. Without any studies on the real carbon impacts of syrup packaging, they were unable to confirm or dispel this theory. Ultimately, the dearth of existing research made it difficult to engage in industry-wide dialogue about choosing more sustainable packaging choices.

Our team determined that we could utilize the inputs from the distribution model to conduct a separate LCA on these different container types to shed light on the systems impacts of packaging choices. Our goal with this project is to better inform industry players in their efforts to reduce the carbon impacts of their supply chains.

In the next section we will delve into our analysis of the maple syrup packaging landscape, and the carbon impact implications of various syrup packaging schemes.

SECTION 2. PACKAGING

I. Maple syrup packaging background

The United States is a major producer of maple syrup, with a total production volume of around 4.2 million gallons of maple syrup in 2022. In 2023, the state of Vermont produced over two million gallons of maple syrup, making it the top producer of maple syrup in the United States. The second leading producer, New York, had a production volume of about 75 thousand gallons of maple syrup in that year (Statista 2023b).

Maple syrup comes in various retail packaging options, catering to both producers' preferences and customer demand. Among the popular choices are plastic, glass, and metal containers, each with its unique advantages and drawbacks concerning syrup preservation during storage. Some characteristics of different types of packaging are:

HDPE plastic jugs

- Commonly used plastic material
- Coated with an oxygen-impermeable barrier to help protect syrup from darkening and flavor changes that can happen in packed syrup over time
- Better adapted to longer storage periods
- Cannot be infinitely recycled

Glass bottles

- The non-porous nature of glass helps in preserving the taste and quality of maple syrup over time
- Can handle high temperature
- Highly reusable, offering consumers the opportunity to repurpose for various uses
- Can be infinitely recycled

A majority of glass bottles are sourced from outside of the United States. According to The Observatory of Economic Complexity (n.d.), the United States imports Glass bottles primarily from Mexico ($553M), China ($456M), Taipei ($131M), Canada ($122M), and Italy ($107M). China was the fastest-growing import market in the United States glass bottles between 2020 and 2021.

II. Literature Review

The literature review was conducted to understand the materials flow and the energy requirements for every stage of the glass and HDPE process. There are no articles that explore the LCA on maple syrup packaging, however, the articles from other LCA beverage packaging are included as the wider beverage market provides applicable and relevant results. The majority of LCA that assessed these packaging materials found that glass can have the highest impact, however, can also be less impactful when reused (Ghenai, 2012; Stefanini, et al., 2021; Ferrara, et al., 2020, Carter, 2022). Based on these studies, regardless of the material, the production of the primary packaging materials is the most impactful stage.

Research indicates that solely considering the packaging production phase, glass bottles are less environmentally friendly compared to PET, HDPE, cardboard, PP bottles, or aluminum cans, particularly concerning the impact on global warming potential (GWP) and cumulative energy demand (CED) categories (Amienyo, et al., 2013, Pasqualino, et al., 2011, as cited in Stefanini, 2021, et al.,). In the transportation phase, it contributes approximately 3% of the total environmental impact, largely due to its considerable weight and dimensions. Across various end-of-life scenarios—recycling, incineration, and landfill—the plastic bottle demonstrates better environmental performance compared to glass. Glass emerges as the most impactful packaging material for all types of beverages, as indicated by Cumulative Energy Demand and Global Warming Potential assessments (Pasqualino et al., 2011, cited in Stefanini et al., 2021).

In a study by Ferrara and De Feo (2020) focusing on wine packaging, reusable glass emerged as the most environmentally preferable material across all impact categories when the transport distance was set to 500 km. However, cartons and plastic bags in boxes were identified as the least environmentally impactful options across all categories. Nonetheless, at distances shorter than 100 km, the environmental impacts of reusable glass bottles become comparable to those of cartons and bag-in-box packaging. When compared with plastic, research by Franklin Associates (2009) revealed that HDPE bottles exhibited lower carbon emissions than glass bottles reused eight times. Although increasing the return rate of glass bottles from 8 to 11.9 reduced emissions, the HDPE bottle still outperformed. Notably, the transport of glass bottles accounted for a significant 25% of energy usage, whereas its plastic counterpart only contributed 5%.

In reality, there is limited practice of returning glass bottles to distributors for refilling syrup, except among some small local syrup producers. Typically, consumers either repurpose the bottles for other uses or return them to local producers for refilling. This trend towards reuse presents an opportunity to reduce material consumption and environmental impact. Therefore, a reuse scenario is proposed to assess the potential emissions and energy savings if a return system were adopted industry wide. Amienyo et al. (2013) found that reusing carbonated drink glass bottles even once could reduce Global Warming Potential (GWP) by 40%. However, the savings percentage plateaus after eight reuses due to the growing significance of bottle transport and cleaning.

III. Methods

a. Life Cycle Assessment

Life cycle assessment is a methodology to assess the environmental impact of a product or process throughout its whole life cycle. An LCA consists of four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation.

Sensitivity analysis

Different scenarios and sensitivity analyses will perform, as provided in the Results section. Scenarios include transporting using different types of vehicles: diesel internal combustion engine heavy-duty truck (ICET), battery electric heavy-duty truck (BET), and hydrogen fuel cell electric heavy-duty truck (FCET) with the fuel mix in 2021 and 2035 to understand what types of vehicles have the most impact on the carbon footprint; different locations of the suppliers to understand how the distance has an impact on the emission; and the number of times the bottle is returned to identify how much change it has on the emissions. Therefore, different values are modeled to understand the effect of these varying parameters.

SimaPro 9.3 (PRé Consultants, 2021) is the LCA software used to model the system with EcoInvent 2.2 and 3.8 databases. The IMPACT 2002+ v 2.15 assessment method is applied to estimate the environmental impacts. Recycling data were obtained from the EPA WARM model (US EPA, 2024a), and transportation and washing emission data were obtained from GREET (Argonne GREET Model, n.d.) and literatures.

b. Assumptions

The key assumptions are as follows:

- Caps and labels are excluded due to a small portion that accounts for weight.
- For commercial reuse, glass bottles are transported back to the glass distributor to clean and then transported to syrup producer/filler to fill the syrup.
- Glass bottles can be washed at both industry and household, while HDPE is only household wash.
- Natural gas is used to heat the drying process.
- For household washing, clean bottles are refilled at the retailer by using a passenger car to travel 12 km.

- Upstream transportation is not included in the main model; however, it is included in the scenario analysis to explain how much impact it has on the emissions.
- Chose Burlington, Vermont as the final retail location since the maple syrup producer is in Strafford, Vermont.
- Short haul - Class 6 are used for transport less than 322 km and Long-haul - Class 8 are used for transport greater than 322 km.
- End-of-life after reuse is assumed to be landfilled since reusing multiple times can affect the quality of the bottle.
- End-of-life for cardboard for shipping materials are recycled and LDPE wraps are landfilled.
- End-of-life waste management locations are based on the average distance from the most populous city in Vermont - Burlington.

c. Systems studied

This model evaluates two common container systems used for maple syrup:

1. 8 fluid oz glass bottle that weighs 0.255 kg
2. 0.5 pint HDPE jug that weighs 0.038 kg

The caps and labels used by the containers are not included in this analysis. Secondary packaging is included in the scope and boundaries. Cardboard and LDPE wraps are used for glass bottles and only LDPE wraps are used for HDPE bottles in secondary packaging. The end of life for secondary packaging is also included in the secondary packaging analysis. Cardboard is assumed to be recycled and LDPE wraps are assumed to be landfilled after single-use.

d. Functional Unit

The functional unit for this LCA is one gallon of maple syrup stored and transported in a bottle. All results are expressed based on this functional unit.

e. System boundaries

System boundaries for glass and HDPE are shown in Figures 14 and 15. The main difference of the supply chain between glass and HDPE is the bottle distributor. Between glass bottle manufacturer and filling, there is a glass distributor while HDPE bottles are sourced directly from the manufacturer according to the interview with the stakeholder. Distribution of glass, filling, retail, and consumption phases are not within the scope of these boundaries. Transportation from the manufacturer to filling is also excluded from this model, as it has been integrated into another model developed by the Center for Sustainable Systems (CSS). Additionally, it is assumed that emissions generated during customer trips from the store are small, as they are allocated to all purchased items in a given trip.

This model includes all processes from the extraction of raw materials through the production of materials in a form ready for fabrication into a maple syrup container, fabrication of containers, and the common end-of-life scenarios of postconsumer which include landfill, incineration, recycling, and the energy requirements for transporting materials to waste management facilities.

Under food packaging regulations, plastic bottles cannot be recycled to produce new food packaging bottles; only virgin materials can be utilized for this purpose. However, it should be noted that plastic bottles can still be open loop recycled into other products.

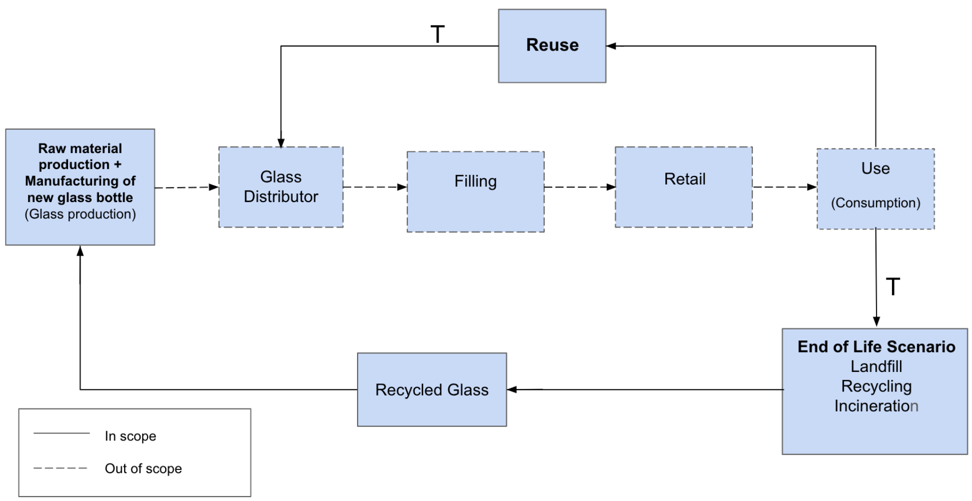


Figure 14: System boundaries for glass bottle

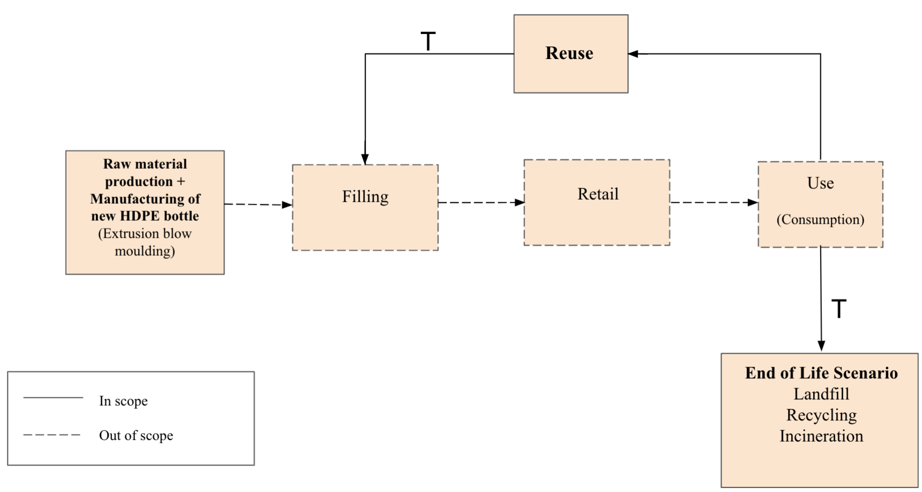


Figure 15: System boundaries for HDPE bottle

f. Impact Categories

The environmental indicators that were considered include total non-renewable energy consumption, and Global Warming Potential (GWP). Total non-renewable energy consumption is the sum of all types of energy used in the lifecycle of a material and is given in units Megajoules (MJ). GWP is the measure of the level of contribution to global warming and is expressed as a factor of carbon dioxide and given in units kilograms of carbon dioxide equivalents (kg CO_2e).

IV. Inventory data

a. Raw material and bottle production

Glass

This step includes the material and energy efforts for the preparation and sorting of cullet, melting, forming of glass containers, cooling down, packaging, and palleting until glass containers are ready for transport to customers. Transports for the input materials are included as well as direct emissions to air, wastewater and waste.

HDPE

This step includes the material and energy efforts to extract the raw materials and manufacture them into the plastic jug. The raw material process includes the extraction of raw materials until delivery at the plant to make the product, and the manufacturing process includes the extrusion of plastic sheets and thermoforming and blow molding to get into a shape. The GHG emission factors and non-renewable energy data for both glass and HDPE are provided in table 8.

Table 8. Energy and GHG emission factors of primary packaging database

Packaging Type	Manufacturing stage	GHG (kg CO_2e /kg)	Energy (MJ)	EcoInvent data
Glass bottle	Production	0.861	15.1	Packaging glass, white, at plant/kg/RER S
HDPE bottle	Raw material	1.74	76.4	Polyethylene, HDPE, granulate, at plant/RER S
	Production-Extrusion	0.984	14.4	Extrusion of plastic sheets and thermoforming, inline |{GLO}|market for |Cut-off,S
	Production-Blow moulding	1.23	20.9	Blow moulding |{GLO}|market for|Cut-off,S

b. Reuse

The model includes industrial washing, following a Business-to-Consumer (B2C) model where customers return empty bottles to be cleaned at the glass distributor and refilled at the packer before being returned to the consumer. Additionally, a scenario is proposed where customers wash bottles at home and return them to packers for refilling. Data on washing inventory were sourced from a study on wine bottles in Italy (Landi et al. 2019). Various studies and references suggest reuse rates between 10 and 30 times. Thus, for this model, we assume a reuse limit of 20 times.

1. Industrial washing

The weight of the 8 oz glass bottle used for this washing inventory is 0.255 kg. The final washing emission is then converted to the Functional Unit which is one gallon.

The weight of a wine bottle used by the analyzed consortium is 0.45 kg bottle and the automatic washing data are as follow:

- Water: consumption of about 90 l per 1 million of bottles, which means 0.00009 l/bottle
- Soap: consumption of about 9 kg of soap per 1 million of bottles, which means 0.000009 kg/bottle
- Electric energy: the machine has an average power absorption of 0.89 kW and the processing time for a single bottle is 30 s.
- Heat for sterilization: consumption of about 170100 MJ per 1 million of bottles, which means 1.7 MJ/bottle
- Electric energy for drying: consumption of about 220 kWh per 1 million of bottles, which means 0.0022 kWh/bottle
- Heat for drying: consumption of about 849600 MJ per 1 million of bottles, which means 0.85 MJ/bottle.

Using the data from the analyzed consortium, the washing data are calculated as follows:

$$Water\ (l) = \frac{0.00009\ l}{0.45\ kg} \times bottle\ weight\ (kg)$$

$$Soap\ (kg) = \frac{0.000009\ kg}{0.45\ kg} \times bottle\ weight\ (kg)$$

$$\text{Electricity}_{\text{Washing}}\ \text{(kWh)} = 0.89\ kW \times 30\ s \times \frac{1\ H}{3600\ s} \times \frac{bottle\ weight\ (kg)}{0.45\ kg}$$

$$\text{Heat}_{\text{Sterilization}}\ \text{(MJ)} = \frac{1.7\ MJ}{0.45\ kg} \times bottle\ weight\ (kg)$$

$$\text{Electricity}_{\text{Drying}}\ \text{(kWh)} = \frac{0.0022\ kWh}{0.45\ kg} \times bottle\ weight\ (kg)$$

$$\text{Heat}_{\text{Drying}}\ \text{(MJ)} = \frac{0.85\ MJ}{0.45\ kg} \times bottle\ weight\ (kg)$$

Figure 16 and 17 show the process for a new use. Washing, sterilization and drying are the phases necessary for reuse. After the bottles are clean, they are transported to the packer-distributor to refill and distribute to the retailers.

In the industrial reuse, only glass bottles are considered for return to the glass distributor to undergo washing and subsequent reuse. The distance of the glass bottle distributor in Lachine, Quebec to packer-distributor at Strafford, Vermont to the national retailer in the populous city of Vermont - Burlington was used for the transportation distance for industrial washing, which has a total of 425 km. After the bottle is used, it is returned to the glass distributor to clean and then refill at the packer-distributor, which will have to travel back for 425 km. After being reused for a certain number of times, it's anticipated that the bottles will be disposed of in a landfill due to the degradation in glass quality.

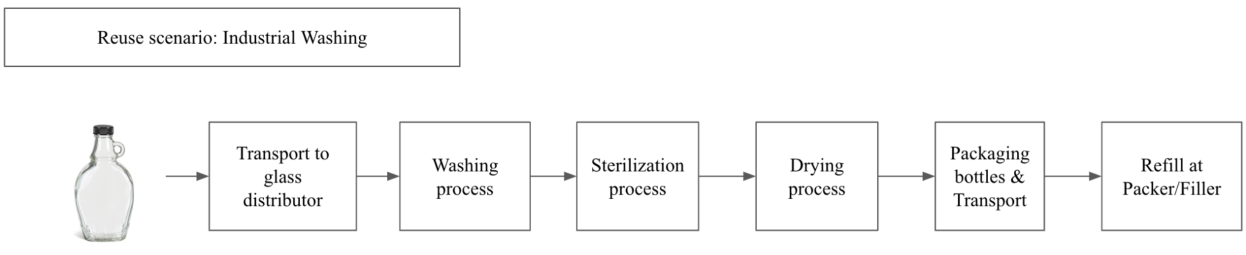


Figure 16. Reuse process for glass bottle industrial washing

2. Household washing

In the household washing scenario, the initial step involves washing the bottles using cold water and soap, followed by air drying. Both glass and HDPE bottles are assumed to undergo this washing process. Once cleaned, consumers then travel to the closest packer-distributor using a passenger car to refill the container. For HDPE bottles, it's assumed that their end-of-life (EoL) after reuse involves being landfilled.

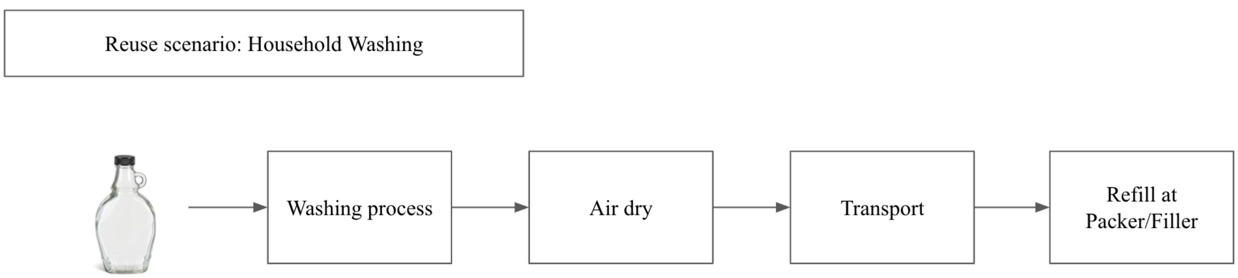


Figure 17. Reuse process for glass and HDPE bottle household washing

Table 9 shows the washing inventory data for the 0.255 kg glass bottle. The washing data are then times with the emission factors and converted to the functional unit, in gallons.

The energy and GHG emission factors were obtained from SimaPro (PRé Consultants, 2021) as shown in Table 10. The emission factor for natural gas was obtained from GREET (Argonne GREET Model, n.d.), which has 0.00634 kg CO_2 e/MJ of emission factor and 0.48 MJ of energy consumption factor.

Table 9. Washing inventory data for 0.255 kg glass bottle

Reuse phases	Resource	Amount	Unit
Washing	Water	5.10E-05	l
	Soap	5.10E-06	kg
	Electricity	8.90E-01	kWh
Sterilization	Heat	9.60E-01	MJ
Drying	Electricity	1.20E-03	kWh
	Heat	4.80E-01	MJ

Table 10. Energy and GHG emission factors database

	GHG		**Energy**		
	Amount	Unit	Amount	Unit	Process
Water	3.07E-04	kg CO_2e/kg	5.55E-03	MJ/kg	Tap water, at user/RER/S
Soap	1.56	kg CO_2e/kg	29.3	MJ/kg	Sodium percarbonate, powder, at plant/RER S
Electricity	4.29E-01	kg CO_2e/kWh	7.29	MJ	Electricity, medium voltage, at grid/US S
Heat	6.34E-02	kg CO_2e/MJ	4.80E-01	MJ	

Note: Data for water, soap and electricity are from EcoInvent data, and data for heat is from GREET.

c. Transportation to EoL

Distances to recycling, landfill, and incineration sites can vary for each customer. Burlington, Vermont, the most populous city in the state, was chosen as the source point. The average distances to waste management sites were calculated using Google Maps. Class 6 trucks are used due to the shorter distance involved. Figure 18 shows the locations of waste management and recycling facilities from Burlington city. The average distances to the end-of-life (EoL) facilities are as follows:

- Recycling center: 9.38 km
- Waste Management: 52.3 km
- Incineration plant: 3.2 km

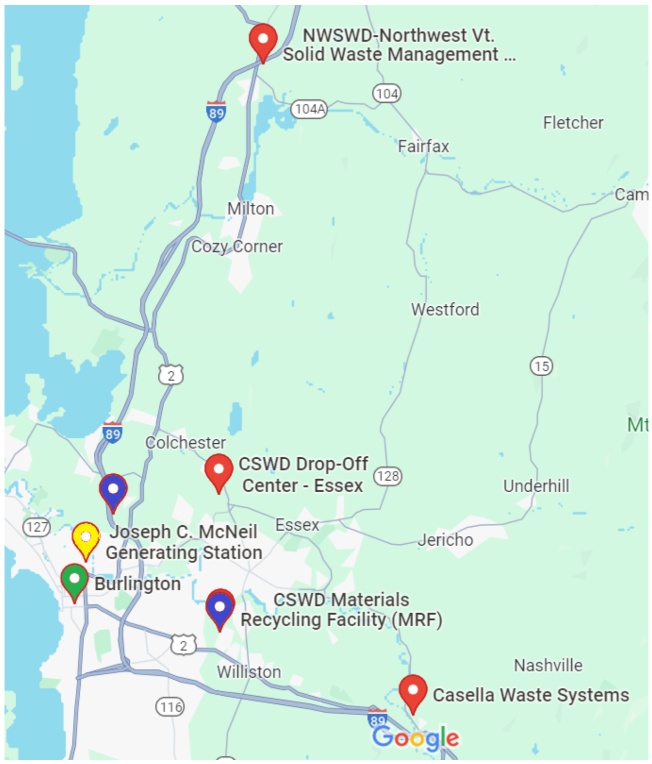


Figure 18. Waste management and recycling site locations

d. Types of vehicles

For transportation, we considered 7 types of vehicles: internal combustion engine truck (ICET), battery electric truck (BET), fuel-cell electric truck (FCET), and passenger car. Specifically, we examined both class 6 and class 8 trucks, with class 6 intended for short-distance transport (less than 322 km) and class 8 for long-distance transport (greater than 322 km). We also considered the future grid decarbonization when calculating the emissions from electric vehicles. See Appendix for the equations.

e. End-of-Life

According to the US EPA (2023b), in 2018, glass achieved a recycling rate of 31.3%, resulting in the recycling of approximately 3.1 million tons of glass containers. Landfills received approximately 7.6 million tons of Municipal Solid Waste (MSW) glass, which accounted for 5.2% of all MSW landfilled in 2018. Additionally, 1.6 million tons of glass were combusted, representing 4.8% of all MSW combustion with energy recovery in the same year.

According to the US EPA (2024b), in 2018, landfill received 27 million tons of plastic, which accounted for 18.5% of all MSW landfilled. The total amount of plastic combusted in MSW was 5.6 million tons, which accounted for 16.3% of all MSW combusted with energy recovery that year. Compared to landfill and combustion, the amount of recycled plastic was relatively small with three million tons for a 8.7% recycling rate. However, the recycling rate of some specific types of plastic containers is more significant - PET bottles and jars were 29.1% and HDPE natural bottles was 29.3% in 2018.

GWP emissions and energy consumption for recycling is obtained from WARM (US EPA, 2024a). Landfill and incineration scenarios are obtained from EcoInvent database: Packaging Waste scenarios. Table 11 presents the emissions and energy consumption database of glass and HDPE in different end-of-life scenarios.

Table 11. EoL emission and energy consumption factors

		Unit	EoL - Recycle	EoL- Landfill	EoL - Incineration
	GHG	kg CO_2 e	-2.80E-04	6.82E-03	2.38E-02
Glass	Energy	MJ	-2.25E+00	1.97E-01	4.97E-01
	GHG	kg CO_2 e	-7.60E-04	6.59E-02	2.99E+00
HDPE	Energy	MJ	-4.73E+01	3.22E-01	2.20E-01

V. Results

a. Life Cycle GHG Emissions

Figure 19 shows the GHG emissions of different bottle types. The life cycle GHG emissions of a glass maple syrup bottle are approximately 5.1 kg CO_2e per gallon. Raw material production and manufacturing process contribute to 68% of total GHG emissions, and shipping materials contribute 31%. Regardless of the different end-of-life scenarios, GHG emissions are similar as the contribution from the EoL phase is negligible. The life cycle GHG emissions for a plastic maple syrup bottle are approximately 4.2 kg CO_2e per gallon if recycled or landfilled after use. The primary contributors to these emissions are raw material production and manufacturing (55%), and shipping materials (45%). However, the GHG emissions will be as high as 5.9 kg CO_2e/gal if incinerated after use. Generally, glass bottles emit more GHG than plastic bottles except for incineration of HDPE bottle.

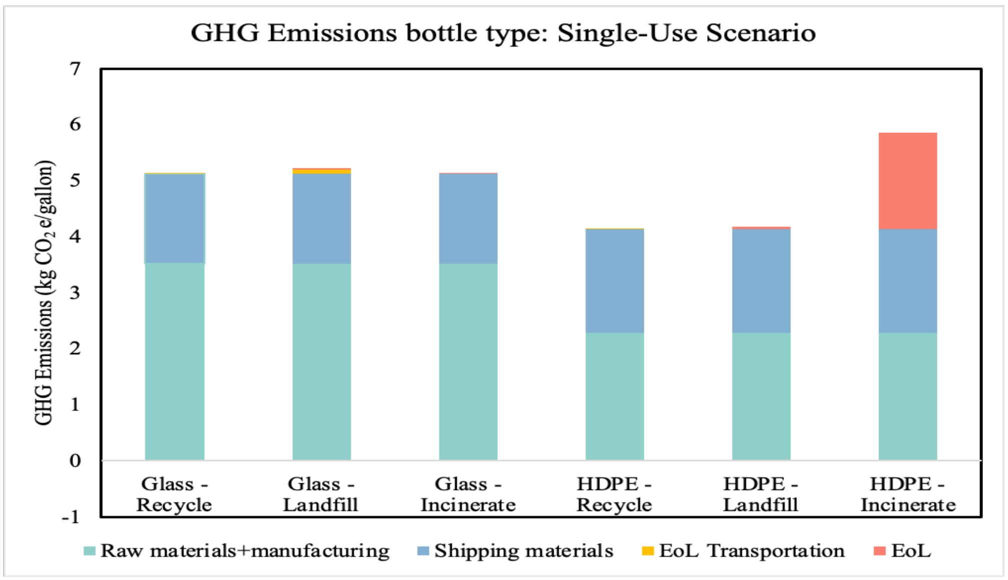


Figure 19. GHG emissions of different bottle types under single use scenario

b. Non-Renewable Energy Consumption

Figure 20 presents the non-renewable primary energy consumption of different bottle types under single use scenarios. This study determines that the life cycle non-renewable energy consumption of a glass maple syrup bottle is approximately 118 MJ/gal if landfilled or incinerated after use or 107 MJ/gal if recycled. Material production, manufacturing, and shipping materials consume a comparable amount of energy. In the case of a plastic bottle, energy consumption is around 150 MJ per gallon if it ends up in a landfill or is incinerated at the end of its life. However, if it's recycled after use, the energy consumption can decrease to as low as 110 MJ per gallon. Throughout its life cycle, the majority of energy consumption is attributed to raw material production, manufacturing, and shipping materials.

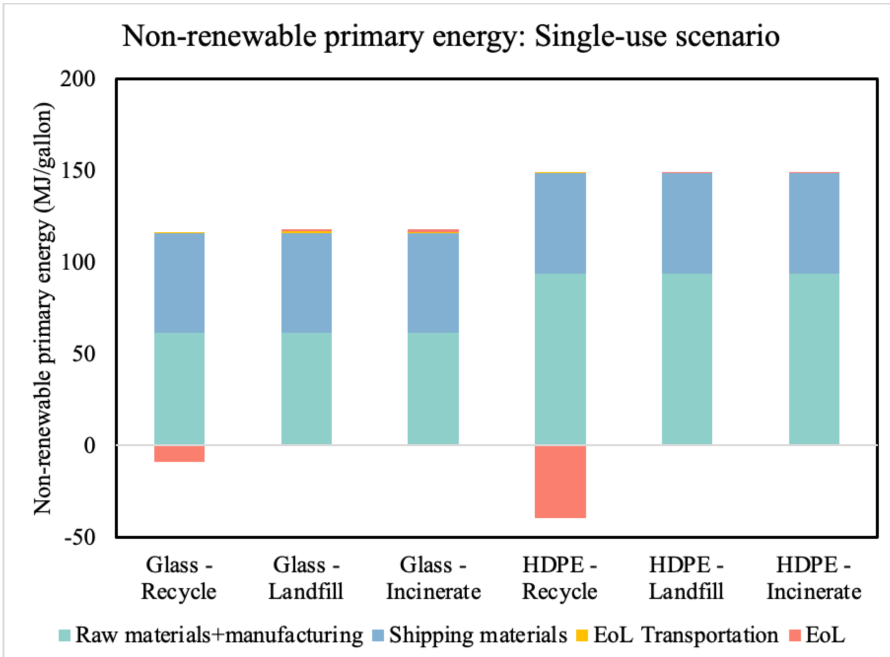


Figure 20. Non-renewable primary energy consumption of different bottle types under single use scenario

c. Scenarios

1. Different Transportation Distances Impact

As shown in figure 21 glass bottles originally manufactured in Asia exhibit significantly larger GHG emissions (9.3 kg CO_2e/gal) compared to glass from Mexico and domestic sources (6.2 kg CO_2e/gal) due to the long shipping distances involved and the heavy weight of glass bottles. Switching from glass bottles from Asia to glass bottles produced in North America would potentially decrease GHG emissions by 33%. In contrast, as shown in figure 22, transportation distances have a minimal effect on GHG emissions for plastic bottles (around 4.2 kg CO_2e/gal) due to their light weight.

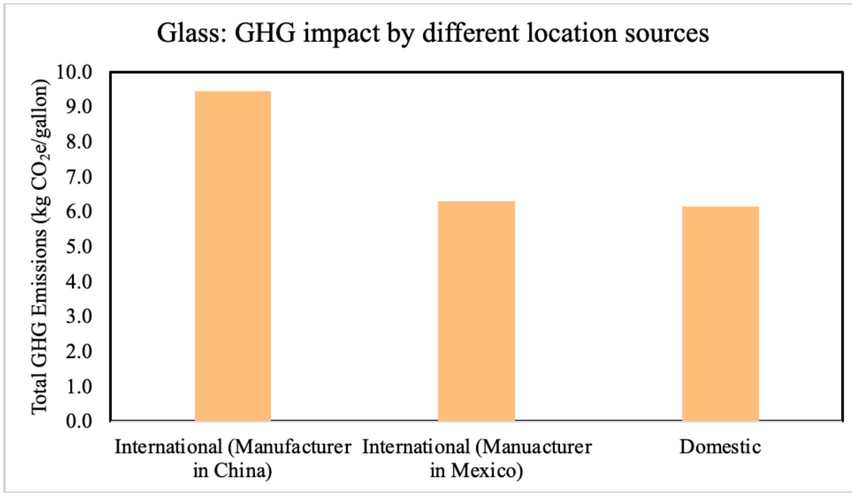


Figure 21. GHG emissions per gallon of glass bottles by different location sources

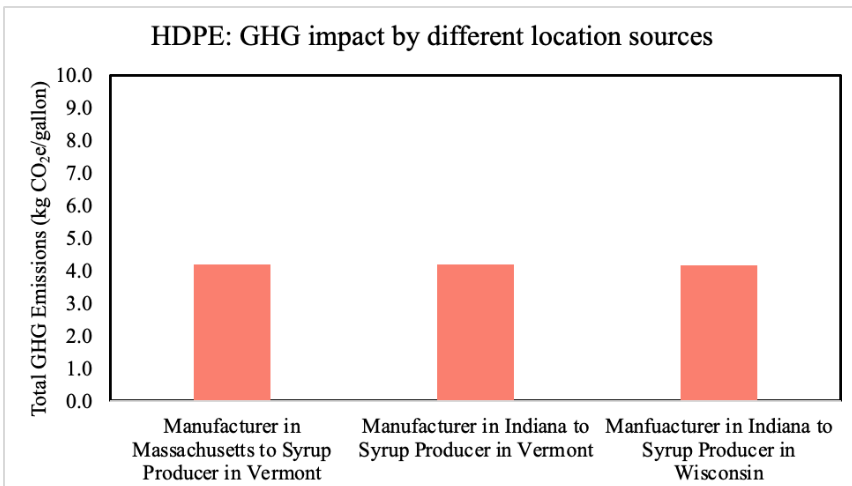


Figure 22. GHG emissions per gallon of HDPE bottles by different location sources

Figure 23 and 24 depicts the non-renewable primary energy consumption of bottles from different sources. Glass bottles manufactured in Asia top the list, which require 144 MJ/gal. By contrast, glass bottles from Mexico and domestic sources have similar energy impacts of 132 MJ/gal. Switching bottle manufacturing from Asia to North America can potentially decrease energy consumption by 8%. HDPE bottles from different sources show comparable energy consumption of approximately 92 MJ/gal.

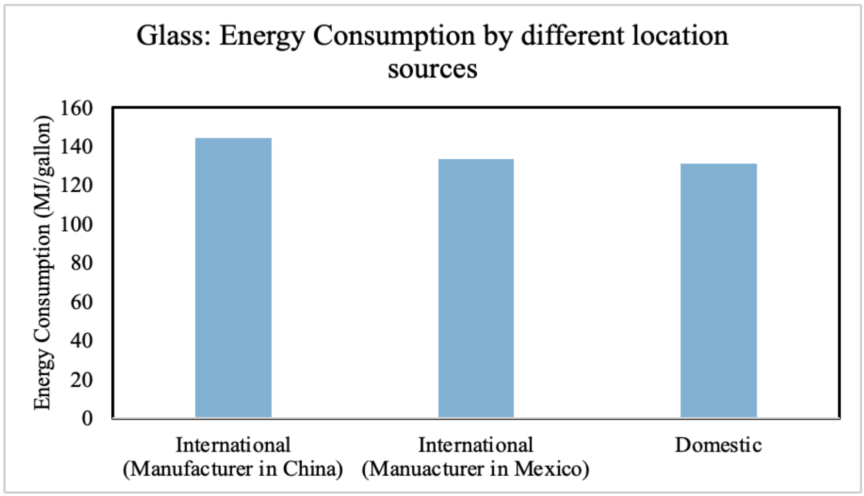


Figure 23. Energy consumption per gallon of Glass bottles by different location sources

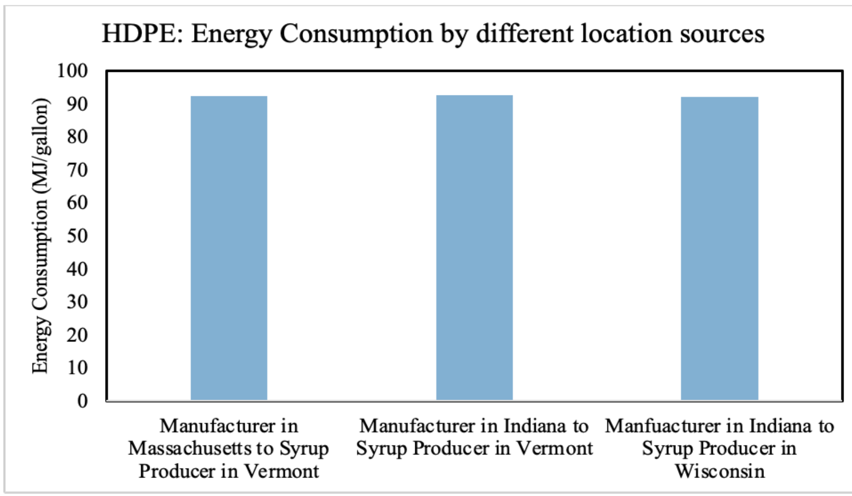


Figure 24. Energy consumption per gallon of HDPE bottles by different location sources

2. Diesel vs Electric vehicle

Figure 25 depicts the different GHG emissions with traditional diesel fueled trucks and electric trucks. GHG emissions from the three types of trucks in 2021 are comparable, with 1.2 kg CO_2e/gal for ICET, 0.9 kg CO_2e/gal for BET, and 1.0 kg CO_2e/gal for FCET, respectively. Considering further grid decarbonization, GHG emissions from the two electric trucks (BET and FCET) will be as low as 0.16 kg CO_2e/gal in 2035, which show great GHG benefits over ICET (1.2 kg CO_2e/gal). In 2035, electrifying a diesel fueled truck can reduce GHG emissions by 87%.

Figure 26 shows the non-renewable primary consumption of different trucks. Of the three types of trucks, FCETs consume the most energy at 26 MJ/gal. In contrast, the energy consumption of ICET and BET is similar, both averaging around 16 MJ/gal.

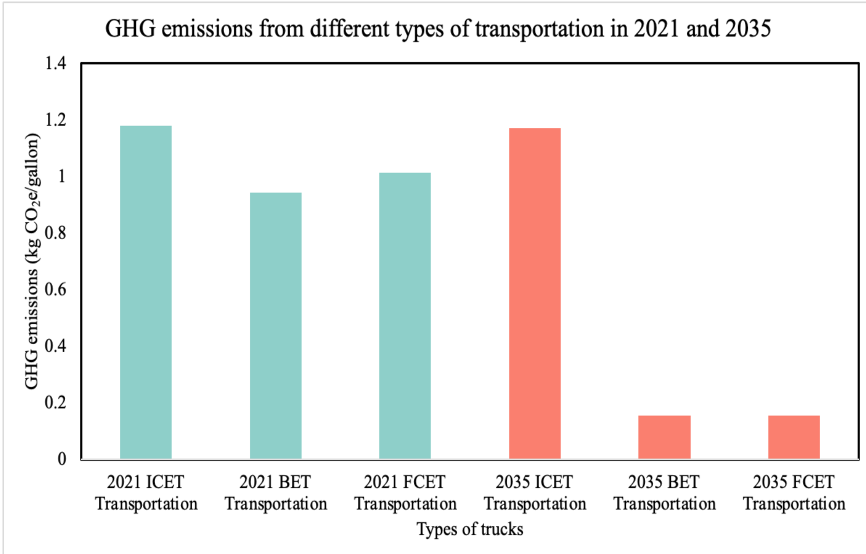


Figure 25. GHG emissions from different types of trucks

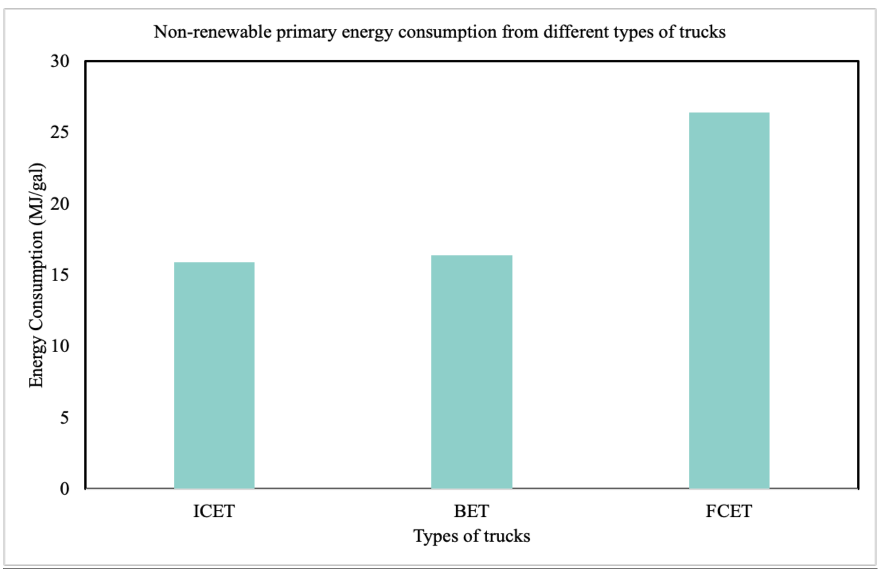


Figure 26. Energy consumption from different types of trucks

3. Reusing Glass vs. Single Use

For single-use scenarios, the Global Warming Potential (GWP) is equivalent to the lifecycle of a non-returnable glass bottle, which involves production, use, and disposal, and upstream transportation. If the bottle is reused three times, it is produced once but used three times. The overall impact of the bottle is the sum of impacts attributed to one production cycle, two washings, one-time upstream transportation, three times transportation to retail after filling, shipping materials, and end-of-life (EoL) transport.

Figure 27 illustrates the GHG emissions and figure 28 illustrates the non-renewable energy consumption comparison between reusable glass bottles, single-use glass bottles with EoL recycling, and HDPE bottles with EoL landfilling. For single-use glass bottles, the most carbon-intensive aspect of the supply chain is typically raw material production and bottle manufacturing, which was expected from the supporting literature review. In EoL for both glass and HDPE, the transportation to the waste management or the recycling center are included. The EoL impacts for single-use glass is relatively low because it is assumed they are recycled, thus receiving EoL credits. For HDPE bottles, it is assumed that they are landfilled since the majority of plastic is going to landfill. Shipping materials are also high due to the fact that they are used one time only and the higher production and end of life emissions of LDPE.

In this analysis, transportation from the manufacturer to the retailer is included, as transportation plays a crucial role in the return of bottles. When a bottle is reused, the emissions from material production and transportation from the manufacturer to the glass distributor are divided by the number of times the bottle is reused. After the bottle is cleaned and refilled, it must be transported each time it is reused, significantly impacting reuse emissions. Therefore, the upstream transportation emissions have decreased compared to single-use but not a significant amount due to the distance. The emissions gap continues to widen between the reusable and single-use systems since the glass bottle only needs to be produced once. In the reusable system, the primary contributors to greenhouse gas (GHG) emissions shift to the processes of washing and shipping materials.

Despite glass having a higher GHG emission impact on manufacturing and transportation compared to HDPE, a glass bottle becomes comparable to an HDPE bottle after seven uses. Reusing a glass bottle five times reduces emissions by about 30% compared to single-use glass bottles. If successfully reused 20 times, emissions decrease by 6% compared to single-use HDPE bottles and by 35% compared to single-use glass bottles. After five uses, non-renewable energy consumption decreases by approximately 35% compared to single-use glass bottles and by 28% compared to single-use HDPE bottles. Both emissions and non-renewable energy consumption plateau after five uses.

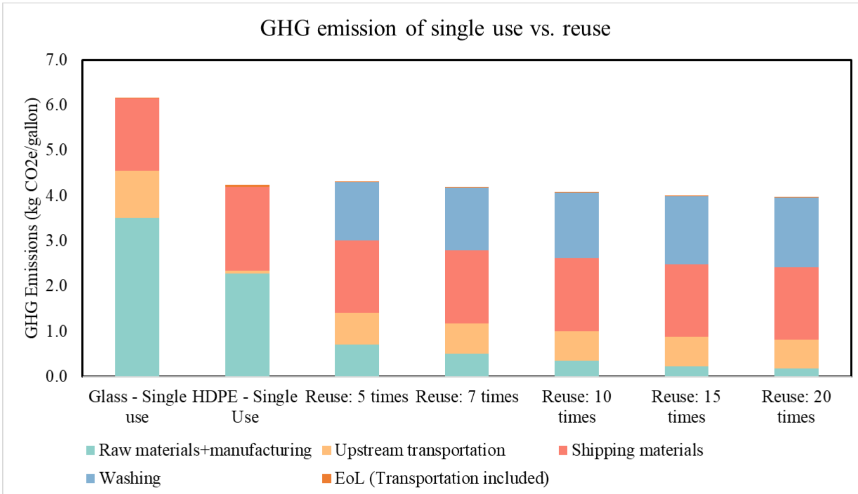


Figure 27. GHG emission per gallon of single use bottle compared to reuse glass bottle

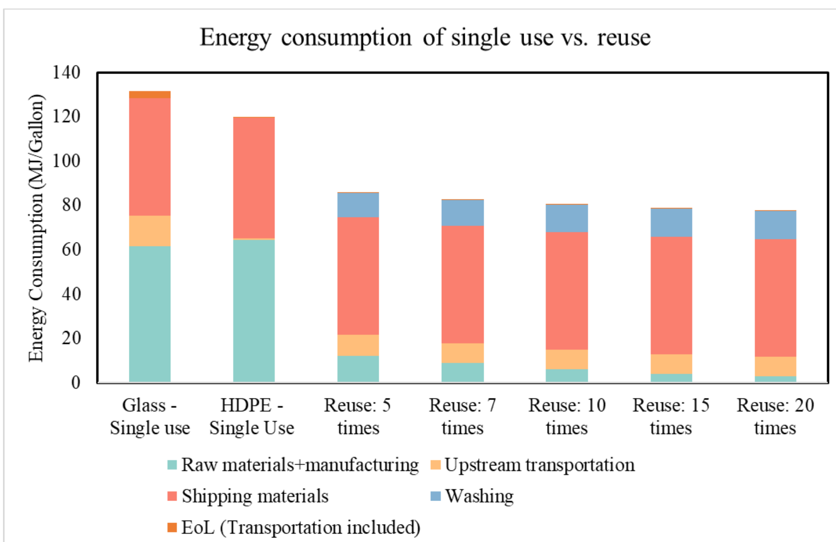


Figure 28. Energy consumption per gallon of single use bottle compared to reuse glass bottle

d. Sensitivity analysis

1. Glass: Multiple uses in household wash

Figures 29 and 30 present the sensitivity analysis of glass bottles to multiple uses in household washing. In household washing, consumers wash the bottles at home using cold water and soap, and then drive to the packer with their own car to refill the syrup. Since there is no sterilization and drying process involved, the washing emissions are lower compared to industrial washing scenarios. However, the most impactful stage in this scenario is transportation.

As detailed in the Reuse vs Glass section, if the bottle is reused over five times, the emissions become comparable to HDPE bottles. Despite the necessity to return the bottles to the glass distributor for industrial cleaning, emissions from long-haul truck transport are lower than those from passenger cars. Thus, in household washing, a distance of 12 km is assumed for consumers to drive back to refill the bottle. Figures 29 and 30 illustrate the GHG emissions and non-renewable energy consumption associated with washing at home.

Due to higher car emissions and the need to drive 12 km solely to refill one bottle, emissions from washing at home and refilling are significantly higher than in industrial washing scenarios. Therefore, even with multiple reuses, which could potentially lower emissions and energy consumption from bottle production and transportation from the manufacturer to the packer-distributor, these benefits are counteracted by the higher emissions from return transportation.

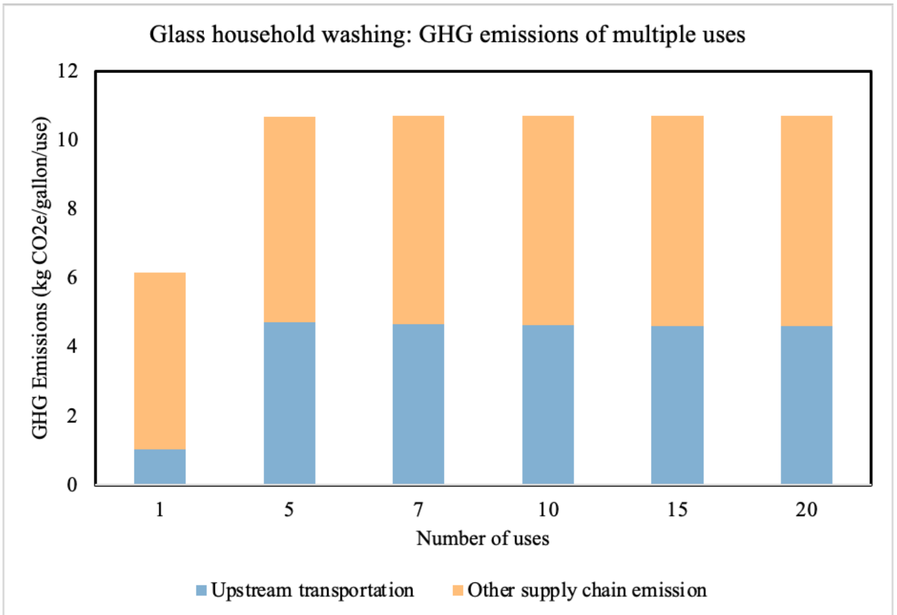


Figure 29. GHG emissions per gallon per use for Glass bottle household washing

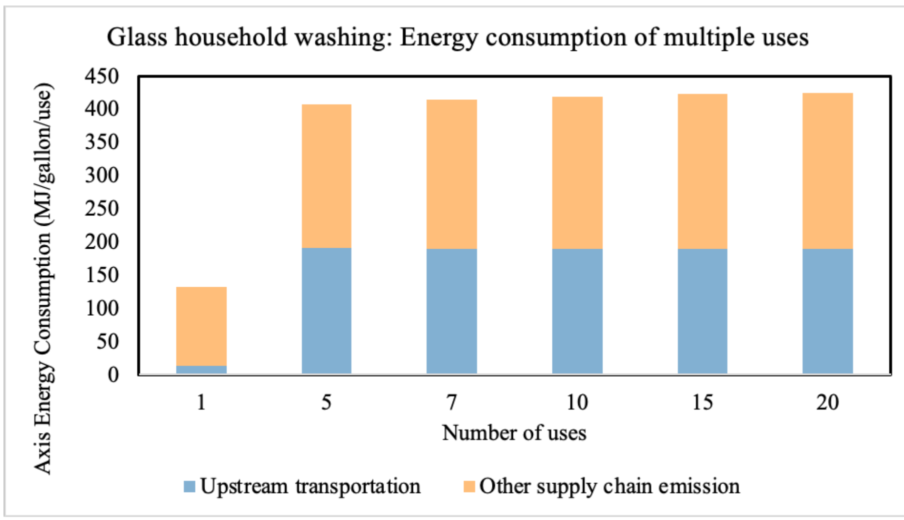


Figure 30. Energy consumption per gallon per use for Glass bottle household washing

2. HDPE: Multiple uses in household wash

Figures 31 and 32 illustrate the impact of reusing HDPE bottles for varying numbers of cycles through home washing. In the reuse scenario, HDPE exhibits lower emissions compared to glass bottles, primarily influenced by the bottle's weight and transportation distances. Even for single-use cases, HDPE demonstrates lower emissions and energy consumption than glass bottles. Upon reaching five reuse cycles, HDPE bottles reduce GHG emissions by 28% and non-renewable energy consumption by 18% per use. Consequently, extended reuse yields even greater benefits. However, reusing HDPE bottles may not be optimal (or allowed), as it can compromise bottle quality, subsequently affecting syrup quality.

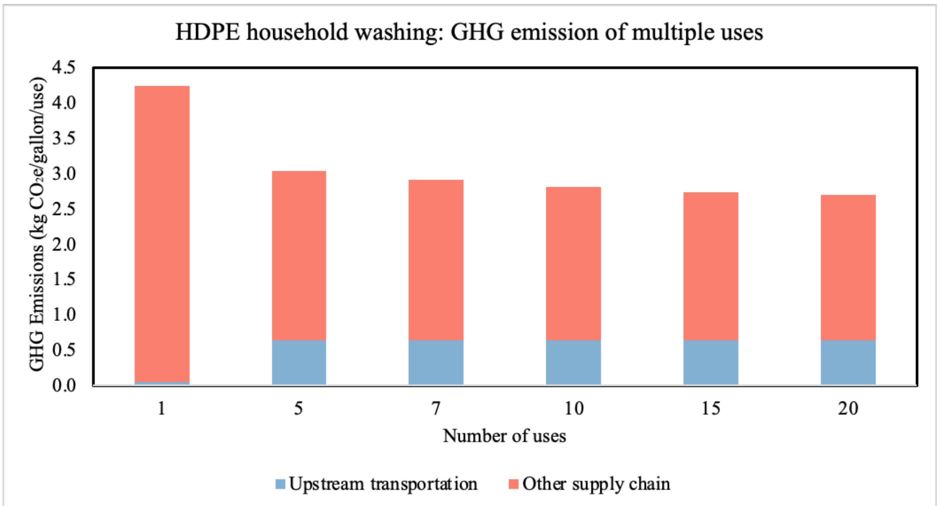


Figure 31. GHG emissions per gallon per use for HDPE bottle household washing

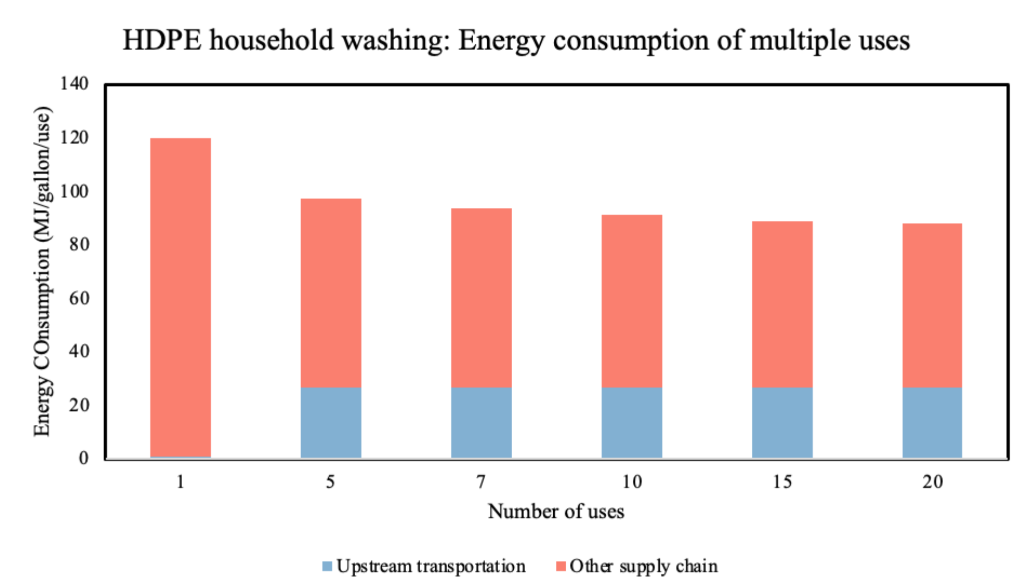


Figure 32. Energy consumption per gallon per use for HDPE bottle household washing

VI. DISCUSSION

The Life Cycle Assessment (LCA) results align with findings from literature analysis, indicating that while glass can have the highest impact, it can also be less impactful when reused. Furthermore, glass bottles exhibit a higher impact in both single-use and reuse scenarios compared to HDPE bottles, primarily due to weight, production, and transportation. The substantial weight of glass bottles leads to increased emissions and energy consumption, as vehicles consume more fuel to transport them.

According to The Observatory of Economic Complexity (n.d.), Mexico and China are the top two glass bottle importers to the United States. Given China's greater distance from the United States, glass bottles must be shipped via sea freight over a considerable distance, then transported using Class 8 trucks to glass distribution centers in the US, and finally to packer-distributors for syrup filling and distribution to retailers. Sourcing glass bottles from Mexico, being closer, results in lower GHG emissions and non-renewable energy consumption during transportation. Local sourcing, such as from New York to the packer-distributor in Strafford, Vermont, further reduces emissions and energy consumption. However, even with local sourcing, glass bottles still exhibit higher emissions and energy consumption compared to HDPE bottles, primarily due to their weight.

All transportation trucks currently operate on diesel fuel, with a high non-renewable fuel mix in the current grid. Utilizing Battery Electric Trucks (BET) and Fuel Cell Electric Trucks (FCET) becomes comparable to diesel, but with the potential for higher renewable fuel mix by 2035, BET and FCET could lower GHG emissions by up to 87%.

When considering single use for glass bottles, emissions and energy consumption are higher than HDPE. In reality, glass bottles are either discarded after a single use, repurposed by households, or refilled at local maple syrup producers. Thus, scenarios proposing the return of bottles to glass distributors for washing and refilling at packer-distributors were explored. The results indicate that reusing glass bottles more than seven times results in GHG emissions comparable to those of single-use HDPE bottles. However, household washing fails to achieve the same goal due to higher car emissions, as trips are solely made to refill a single bottle, resulting in a higher environmental impact. Conversely, since HDPE bottles already have lower environmental impacts than glass, reusing them multiple times can yield even greater benefits.

CHAPTER 3

MITIGATING WASTE AT THE SUGARBUSH

The fourth and final section of our capstone work focused on waste by-products generated at the sugarbush. Our interviews with producers in 2023 revealed two waste streams of primary interest to the sugaring community:

1. Accumulating plastic tubing waste from sap line replacement.
2. Permeate water from the Reverse Osmosis (RO) concentration process.

These two by-products have distinctly different characteristics and root causes, but addressing both of them is key to implementing a holistic impact reduction strategy at the sugarbush. We will first discuss the challenges of managing plastic tubing waste and potential mitigation tactics in current and future waste management landscapes. The second part of this chapter dives into the RO process and investigates whether maple producers should treat permeate as a waste stream or benign system by-product. Research on waste management challenges and proposed solutions was largely conducted through interviews with industry professionals and researchers at agricultural extensions in the United States.

I. Plastic waste at the sugarbush

In the public consciousness, maple syrup tapping conjures images of sap dripping from metal taps into buckets hanging on trees. In 2024, commercial sap collection is a much more sophisticated process involving a network of plastic taps and tubes that convey sap from the forest to the sugarhouse. Drop lines connect each spile (or tap) to a lateral line that connects to a main line, which will eventually channel all of the sap to storage tanks in the sugarhouse. This process is often enhanced through the use of vacuum pumps.

The Maple Guild, one of the largest sugaring operations in Vermont – with close to half a million taps on 24,000 acres of land – runs over six thousand miles of this tubing through the sugarbush to pump stations where the sap is concentrated using RO (Insider Food, 2019). While the majority of sugar makers operate on a much smaller scale, producers typically run thousands of feet of tubing to traverse variable terrain and connect the tapped maple trees dispersed across their sugarbush. Sap lines must be made of food grade plastics to meet FDA production standards. Drop lines and lateral lines are typically made from flexible LDPE tubing in either 3/16" or 5/16" diameter (Roth Sugar Bush, n.d.), while mainlines range from 1/2" to 1" in diameter and are commonly made from more rigid HDPE or PVC plastics.

Maple producers aim to extend the useful life of their tubes for as long as possible, for both economic and environmental reasons. However, the intended life expectancy of these tubes is often cut short due to internal contamination from microbial growth or external interference from pests and natural elements. Once a tube suffers damage, either the whole line must be replaced or a section can be removed and reattached to the network with joints, depending on the nature of the damage (Hedding, 2023). In consulting with industry professionals this study has estimated the drop lines are replaced every 1-3 years, lateral lines are replaced every 10 years, and main lines are replaced every 25 years (Farrell, 2023).

The amount of tubing used at every sugarbush is as variable as the sugarbush itself, each with its own unique makeup of topography and maple tree distribution. However, a simple model (Checkoway, 2024) estimates that on average a sugarbush will need to replace 425 kg worth of plastic tubing over the course of a maple season. Considering the over 9,000 registered sugar producers in the United States, this equates to 3.8 million kg of plastic tubing exiting the system as waste every year. With no readily available end-of-life solutions for discarded tubing, it sometimes accumulates at the sugarbush for years before being carted to a landfill.

It is no wonder then that plastic waste was one of the most cited environmental issues plaguing the maple syrup industry in the course of our interviews with producers and Trade Association specialists. When asked what information they hoped this Acer study could provide to help reduce their environmental impacts, almost all producers desired better guidance on sap line maintenance and plastic waste management. The issue of tubing waste is both highly visible and ever-present. There is broad recognition within the community that it is a mounting problem, but little insight on how to deal with discarded tubing.

II. Reverse osmosis permeate at the sugarhouse

The other by-product of interest to producers is RO permeate, the water that comes out of the RO production process. Reverse Osmosis is a technology for which one of the most common applications is water purification in regions where tap water has undesirable contaminants. In RO machines, pressurized liquid is passed through a series of membranes, separating out pure water from other substances. In the case of maple syrup production, it is this "other substance" that is of real value here: sap concentrate.

A brief overview of the maple sugaring process is required to fully understand the impact of RO technology on the maple syrup industry. The sap that comes out of maple trees is largely water, with a sugar content of 2% (or 2°Brix) on average. In order to be considered maple syrup this sap must be concentrated to between 66° and 68°Brix (Weaver et. al. 2020). Too diluted or two concentrated and the product is no longer sellable on the syrup market. On average 40 gallons of sap are required to produce 1 gallon of maple syrup (Minnesota DNR, n.d.).

Traditionally, once sap is transported from the trees to the sugarhouse it is boiled in a fuel-powered evaporator that runs nonstop while sap is flowing to maximize syrup production. This is a lengthy process. One gallon of maple syrup concentrated solely via evaporation takes around one hour to produce. RO, when used, precedes this process to bring the syrup up to anywhere from 4° to 20°Brix prior to entering the evaporator. Sap can be passed through an RO machine multiple times to increase the concentrate levels as desired. However, currently syrup is still finished via evaporation in all use cases that we are aware of.

RO machines can remove as much of 75% of the water from sap before it enters the evaporator, drastically reducing the time and energy required to produce syrup. The pure water that is removed during the RO process is called the permeate. Even a small-scale RO machine that raises sugar content from 2° to 4°Brix will cut boiling time in half, reducing labor requirements at the sugarbush, which can provide huge relief to producers during the grueling maple season. Though RO machines do use energy, they remove water from sap much more efficiently than evaporation and drastically reduce the energy needed in the evaporation phase to create syrup. Overall, the use of RO can reduce energy consumption associated with syrup production by as much as 70% (Sanford, 2003). Figure 33 shows a simplified diagram of sap moving through the RO process.

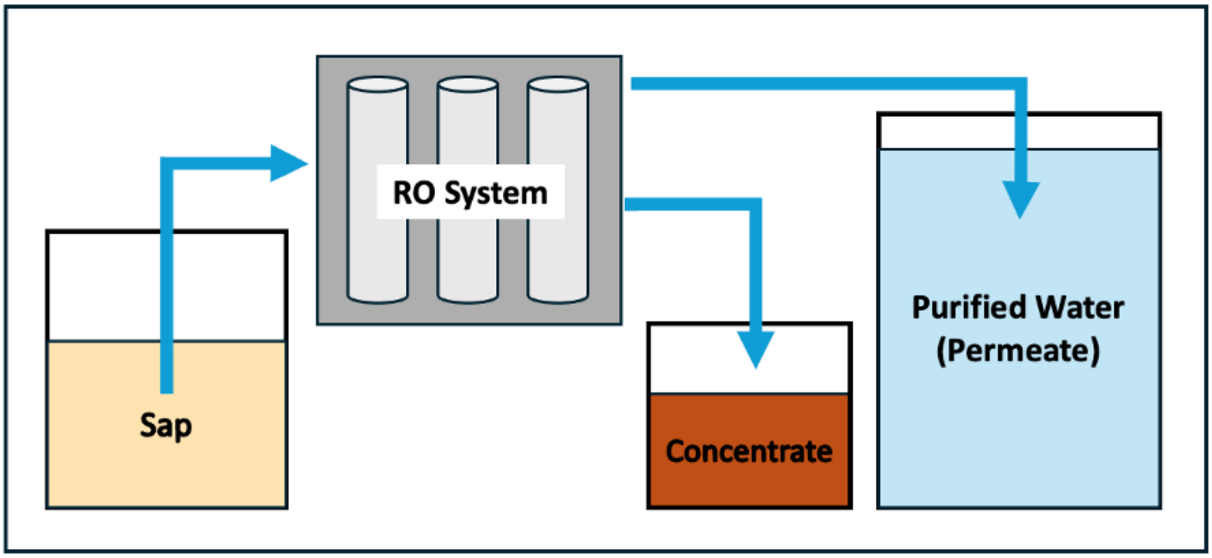


Figure 33. Simple Diagram of a Reverse Osmosis System

If RO has so many benefits why aren't all producers using it? The first, and perhaps most obvious barrier is cost. RO equipment is expensive and may only make sense to purchase if the sugarbush can benefit from economies of scale. RO machines may also require a certain volume of flow in order to function. As such, small scale producers with variable sap flows might not be able to make consistent use of an RO machine.

The other, less apparent barrier to RO adoption that emerged through our interviews with producers were concerns over by-products coming out of the RO system. The first of these by-products is paper filter presses that collect nitrate sugar sand as sap moves through the RO membranes. These filters get replaced after every pass of sap through the RO machine, producing significant sugar paper waste (Miller, 2023).

The second key by-product that is garnering more attention from the producer community is the purified water (permeate) generated by the RO process. Producers didn't have exact measures for the amount of permeate that flows out of RO systems, but the prevailing sentiment was that RO could produce thousands of gallons of water by-product for large-scale producers. We worked with the Center for Sustainable Systems to devise a rudimentary tool that would allow us to quantify the scale of this waste more accurately. We found that a large-scale sugarbush producing 5,000 gallons of syrup per year and concentrating sap from 2° to 20°Brix via RO (requiring multiple passes through RO membranes) would generate 180,000 gallons of permeate; enough water to fill nine average sized in-ground swimming pools.

While generating purified water at the sugarhouse may not appear to be an environmental issue, a number of producers expressed concern due to the unfamiliar nature of this by-product. When using the traditional method of boiling sap, all excess water is released as steam into the atmosphere and does not have to be considered as a potential waste stream at the sugarhouse. A system that generates a liquid by-product, by contrast, may have to be managed in accordance with existing regulation. This uncertainty acted as a deterrent for some producers when considering whether to invest in an RO system (Ferrare, 2023).

A key insight from the CSS LCA is the efficacy of RO in reducing energy use. However, if producers who are already aware of RO's benefits are hesitant to adopt RO due to lack of clarity around permeate management, then this study has not effectively addressed the root of this problem. Recommendations must ideally be delivered hand-in-hand with transparent information that addresses potential barriers to these solutions.

What we ultimately found is that RO permeate, if uncontaminated by cleaning agents or other chemicals, likely does not require a tailored management solution in states where syrup production is prevalent. There are no indicators that releasing this permeate water in its purified state would violate Clean Water Act (CWA) standards, which is the primary regulatory framework that would apply to such by-products. Responsible disposal of permeate would mainly entail discharging water when the ground is thawed rather than frozen, and avoiding discharge directly into surface water like creeks and ponds.

Regulatory concerns begin to apply if the RO permeate is used for washing at the sugarbush, which it often is. If producers are using chemicals like lye or phosphoric acid to clean RO machines and evaporators, then this water would need to be neutralized or otherwise treated before being released to adhere to CWA protocols (Love, 2023). However, the regulation around chemical discharge would apply whether the water used in the cleaning process came from RO, a well, or a municipal water supply. It is worth noting that it is not the permeate that requires careful management as much as any substances added to the permeate before it is disposed of.

Clear and consistent communication around this issue from trade associations and educators may be needed to dispel existing concerns around RO implementation and permeate. That said, for producers who want to implement *best practices* around water discharge, we also explored alternative solutions for handling permeate. In the next section we delve into methods for tackling both plastic waste and permeate management.

III. Guidance for managing waste by-product at the sugarbush

There are a number of tactics that can be used to handle plastic waste and permeate coming out of the maple production process, both in the present and looking towards the future. To consider these recommendations fully we will employ a classic sustainable waste management framework: Reduce, Reuse, and Recycle.

a. Reduce

Plastic

The most effective way to reduce plastic tubing waste coming out of the sugarbush is to extend the useful life of sap lines through careful maintenance practices. Decreasing the replacement rates for sap lines minimizes both waste and overhead costs for maple producers. Sap line configuration and cleaning practices can both impact the effective life of tubing.

When planning sap line infrastructure, producers should consider strategies for preventing impairments caused by pests and the elements. One practice we learned about from our interviews is wrapping drop lines around tree trunks rather than letting them hang down free from the tap. Drop lines can be especially vulnerable to damage due to their placement and the thickness of LDPE material. They may get punctured from animal activity like climbing squirrels, natural occurrences like falling branches, or other interference. When coiled around the trunk of the maple tree, drop lines are less susceptible to these damaging events. Another practice that can minimize damage from the elements is running main lines underground rather than suspended in the air (Hedding, 2023).

Regular cleaning of tubing at the end of every season is also key to longevity to prevent microbial growth in tubes and clearing out microbes when necessary. Microbe contamination is an especially prevalent issue in drop lines and at junctions connecting lines, where exposure risk to the outside environment is highest. Choosing the right cleaning solution is also important. Since sap lines are considered food grade equipment there are tight federal regulations around permissible cleaning agents. However, chlorine – an approved and commonly recommended cleaning agent – attracts animals due to its salt content. Squirrels have been known to chew through sap lines during the cleaning process, counteracting the preservative effects of tube disinfection. One producer we spoke to suggested sodium hypochlorite used in dairy industry applications as an effective and low-maintenance sanitizer that may attract less animal activity due to its quick evaporation time. While alcohol is a popular cleaning agent in the Canadian Maple Syrup industry and it does not have the same associated pest issues, it is not approved in the US as a cleaning agent for food grade equipment.

b. Reuse

<u>*RO Permeate & Plastic*</u>

A number of creative solutions for plastic and RO permeate reuse, outside of equipment and sugarhouse cleaning applications, came up in the course of our interviews.

1. Utilize Tubing for Irrigation

Adam Wild, Director of the Cornell University Maple Research Forest and specialist with the Cornell Maple Program, proposed a particularly interesting solution for both plastic and permeate reuse (Wild, 2023). If pooling surface water from permeate discharge is a concern, decommissioned sap line tubing could be used to disperse this water throughout the sugarbush. Essentially, this practice would cycle the water back into the forest, returning it to the maple trees that it was originally drawn from. It is an elegant solution that provides a second life for tubing with minor damage that is no longer usable for sap collection but may be suitable for irrigation.

2. Wetlands Creation

One producer we spoke to, who wished to remain anonymous, revealed that they had taken the novel approach of experimenting with mini-wetlands creation to mitigate the large amounts of surface water discharge from RO. This tactic would certainly require more thoughtful planning and management than a simple irrigation scheme, but it is worth highlighting for producers that have interest in land management and discharge volumes that may benefit from this solution.

3. Use RO Permeate for Drinking Water

Permeate is potable, free of contaminants, and may be used as drinking water for both employees and customers at the sugarbush. Sugar makers might also consider bottling and selling this water as a retail product. Permeate could be handled similarly to bulk syrup, in that it would be aggregated by a packer that can bottle the water and sell it at scale to retail customers. This option, in addition to generating a new revenue stream for maple producers, avoids discharge-related erosion and pooling issues while adding storage and transportation issues.

One company already sourcing permeate from producers to make a flavored sparkling beverage is Asarasi. The company markets permeate as "tree water" extracted from maple sap through the reverse osmosis process (ASARASI – Pure Water From Living Trees, n.d.). The sixth generation sugarmakers at Branon Family Maple Orchards in Vermont similarly founded the flavored sparkling RO water brand Trētap in 2012 (2014). Today the company is owned by The Forest Farmers, a large-scale sugaring operation in Vermont with over 250,000 taps (Trētap, n.d.).

c. Recycle

While we were not able to find a current recycler that is able to accept used HDPE, LDPE, and PVC tubing at a scale required to meet maple industry needs, there are promising signals that recycling options will exist in the future. As Extended Producer Responsibility laws gain traction across the US and the globe, there is mounting interest from Material Recovery Facilities and private corporations in expanding domestic US recycling infrastructure. One Fortune 500 company making notable investments in plastic recycling capabilities is Republic Services. In 2023, the company announced that it would open its first Polymer Center, a facility designed to process PET and color-sorted HDPE into flakes for new plastic packaging (Republic Services, 2023) and are hoping to expand these Centers across the United States. Since HDPE maple tubing is typically sold in only a few generic colors, tubing discard may be a suitable feedstock at these facilities. We foresee opportunities for similar partnerships continuing to emerge as policies incentivize or mandate use of recycled materials in products.

The only way for syrup producers to meet this opportunity effectively is through collective action and information sharing. At the moment, the size of the plastic waste problem in the maple syrup community is extremely difficult to quantify. Without voluntary disclosure it is impossible to know exactly how frequently producers are replacing lines or how many years' worth of discarded plastic tubing is stored on sugarbush properties across the US. To capitalize on growing demand for recyclable plastics, producers will have to come together to align on the supply that is available.

This process will require facilitation by organizing bodies, industry players, and possibly online platforms for self-reporting. We believe that maple trade associations will have a vital role to play in moving this effort forward. If the adage "what gets measured, gets managed" is true, then accurately measuring the plastic waste problem is a critical first step to implementing long-term solutions.

RECOMMENDATIONS

Given the significant role of maple trees amidst climate change scenarios, preserving maple forests for syrup production instead of harvesting them for wood contributes to climate mitigation by facilitating carbon sequestration and storage. While maple forests represent a substantial potential carbon offset source, engaging in carbon markets requires comprehensive consideration. Challenges such as carbon accounting and verification complexities, as well as associated costs and other difficulties, should be thoroughly evaluated before participating in carbon markets.

To approach the climate change effects on maple syrup production, we recommend producers enhance sap collection by increasing the number of taps and using tubing and vacuum systems. We also suggest producers consider red maples given its better performance in climate change. Silvicultural practices are also important. Producers should maintain soil health to support optimal tree growth and diversify tree species to enhance ecosystem resilience and biodiversity. Monitoring the health of tree crowns enables early detection of disease or stress, while assessing light competition ensures trees receive sufficient sunlight for robust growth. Additionally, tracking tree diameter growth helps assess the overall health and development of the forest stand.

Regarding packaging, while glass bottles might appear more sustainable than plastic ones, their heavier weight results in higher emissions from transportation. We recommend that packer-distributors and producers prioritize reducing the weight of glass bottles, as this has a notable effect on emissions. Secondly, efforts should be made to source from local suppliers, as distance significantly impacts emissions. Thirdly, although diesel and electric trucks currently have similar emissions, it's important to recognize that with near-term decarbonization plans, electric trucks could substantially decrease emissions. Lastly, while implementing reuse and return programs is beneficial, it's crucial to consider transportation emissions associated with commercial cleaning processes, especially for long-distance transportation. Thus, prioritizing local suppliers becomes critical in these scenarios. For consumers, we suggest reusing and refilling bottles at nearby maple syrup producers or reusing them at home for other uses. Additionally, using cold water when washing bottles at home can help reduce energy consumption. However, it's necessary to avoid making special trips solely to refill a bottle to minimize transportation-related emissions.

We have also compiled guidance for producers in managing waste products effectively. First, reducing waste involves optimizing sap line longevity through meticulous cleaning, maintenance, and installation practices. Second, reusing materials plays a crucial role; old tubing can be reused for irrigation to prevent erosion and efficiently cycle water back into the maple forest. Additionally, Reverse Osmosis (RO) permeate can be used for on-site applications such as cleaning, washing, and even drinking water. Exploring alternate revenue streams for RO wastewater, such as bottling for retail, could also be beneficial. Third, recycling initiatives can be enhanced by forming partnerships with waste managers committed to expanding domestic recycling infrastructure. Coordinating waste management needs can help align the growing demand for recycled HDPE and LDPE feedstock with producer supply. It's worth noting that the extent of waste varies significantly from region to region due to differences in tubing quantities, replacement rates, and other factors, making it essential to adapt strategies accordingly.

KEY TAKEAWAYS

Based on our finds and recommendations, our main key takeaways are as follows:

1. Carbon
   Given climate change's impact on maple syrup production—shortening sap seasons, altering habitats, and reducing sugar content—it's imperative to prioritize silvicultural and operational management strategies for increasing productivity.

2. Packaging
   To maximize carbon impact reductions, the maple industry needs to look beyond the sugarbush to their upstream packaging suppliers and downstream distribution partners. Lightweight, locally sourced packaging materials and efficient transport should be prioritized. Packer-distributors will play a key role in leading this space.

3. By-product waste mitigation
   By-products of the maple production process must be thoughtfully managed as part of a comprehensive impact reduction strategy.

APPENDIX

We use the following equations to calculate the GHG emissions from different vehicles.

GHG_{truck}=Emissions Factor * Distance * Weight
$GHG_{passenger\_car}$=16*$Emission_{gasoline}$/(Fuel $Economy_{passenger\_car}$*Energy $Content_{gasoline}$)*Distance

Where:
GHG_{truck}=GHG emissions from transporting one gallon of maple syrup with truck, kg CO_2e/gal,
Emissions Factor=life cycle GHG emissions from transporting one ton of goods for one mile with truck, kg CO_2e/US ton-mile,
GHG_{truck}=GHG emissions from transporting bottle to the distributor, kg CO_2e/gal,
$Emission_{gasoline}$=life cycle GHG emissions from consuming one gallon of gasoline, kg CO_2e/mmBtu,
Fuel $Economy_{passenger\_car}$=the average fuel economy of cars in the U.S., 24.2 miles per gallon,
Energy $Content_{gasoline}$=the energy content of one gallon of gasoline, MJ/gal,
16=the amount of 8oz bottles per gallon.

The variables values are listed in table 12.

Table 12. Emissions and energy content data

	Amount	Unit	Source
$Emission_{gasoline}$	98.2	kg CO_2e/mmBTU	US EPA, 2024c
Energy $Content_{gasoline}$	121	MJ/gal	(US EIA, n.d.)
Energy $Content_{diesel}$	144.9	MJ/gal	

Table 13. Emissions by different vehicles types (Iyer et al., 2023)

Class types	Truck types	Year 2021 (kg CO_2e/ton-mile)	Year 2035 (kg CO_2e/ton-mile)
	ICET	5.20E-01	5.18E-01
Class 6	BET	2.05E-01	3.37E-02
	FCET	2.28E-01	4.88E-02
	ICET	9.44E-02	9.38E-02
Class 8	BET	8.27E-02	1.43E-02
	FCET	8.85E-02	1.43E-02

Table 14. Fuel economy and payload for different vehicles (Iyer et al., 2023)

Class types	Vehicle types	Fuel Economy (mile/gallon)	Payload (lbs)
	Passenger car	24.2	-
	ICET	6.47	7716
Class 6	BET	26.06	7716
	FCET	16.28	7716
	ICET	6.42	38080
Class 8	BET	14.97	38080
	FCET	7.91	38080

We calculate the non-renewable energy consumption with the following equations:

$Energy_{diesel\_truck}=1.2*Energy\ Content_{diesel}/Fuel\ Economy_{diesel\_truck}/payload*Weight*Distance$
$Energy_{electric\_truck}=2.42*Energy\ Content_{diesel}/Fuel\ Economy_{electric\_truck}/payload*Weight*Distance$
$Energy_{passgener\_car}=1.24*Energy\ Content_{gasoline}/Fuel\ Economy_{passenger\_car}*Distance$

Where:
$Energy_{diesel\_truck}$=the non-renewable energy consumption to deliver one gallon of maple syrup with diesel-fueled truck, MJ/gal
1.2=the ratio of primary energy to diesel combustion energy,
$Energy\ Content_{diesel}$=the energy content per gallon of diesel, MJ/gal

Fuel $Economy_{diesel\_truck}$=the fuel economy of diesel trucks, mile/gallon,
payload=the weight of goods that a truck carries, lbs,
$Energy_{electric\_truck}$=the non-renewable energy consumption to deliver one gallon of maple syrup with electric truck, MJ/gal
2.42=the ratio of primary energy to the electricity,
Fuel $Economy_{electric\_truck}$=the fuel economy of electric trucks, mile/gallon,
$Energy_{passgener\_car}$=the non-renewable energy consumption to deliver one gallon of maple syrup with passenger car, MJ/gal
1.24=the ratio of primary energy to gasoline combustion energy,
Energy $Content_{gasoline}$=the energy content per gallon of gasoline, MJ/gal

REFERENCES

Amienyo, D., Gujba, H., Stichnothe, H., & Azapagic, A. (2013). Life cycle environmental impacts of carbonated soft drinks. *International Journal of Life Cycle Assessment*, *18*(1), 77–92. https://doi.org/10.1007/S11367-012-0459-Y/METRICS

Anderson, C. *Food Safety Coordinator*, Anderson's Maple Syrup. Personal communication. July 18, 2023.

ASARASI – Pure Water From Living Trees. (n.d.) Retrieved April 22, 2024, from https://asarasi.com/

Argonne GREET Model. (n.d.). Retrieved December 3, 2023, from https://greet.anl.gov/

Atlantic Corporation. (September 2019). *Maple Syrup Markets & Growth Opportunities: Prepared for Vermont Agency of Agriculture, Food, & Markets*. Retrieved May 18 2023 from https://agriculture.vermont.gov/form/maple-syrup-markets-growth-opportunities.

Bal, T. L., Storer, A. J., & Jurgensen, M. F. (2018). Evidence of damage from exotic invasive earthworm activity was highly correlated to sugar maple dieback in the Upper Great Lakes region. *Biological Invasions*, *20*(1), 151–164. https://doi.org/10.1007/S10530-017-1523-0/METRICS

BascomMaple. (n.d.-a). *Drums & Drum Supplies*. Retrieved April 18, 2024, from https://bascommaple.com/collections/drums

BascomMaple. (n.d.-b). *Bascom Maple Farms 2023 Product Catalog*. Retrieved April 18, 2024, from https://bascommaple.com/pages/bascom-maple-farms-2021-product-catalog

Blain's Farm & Fleet Blog. (2015). *Soil Health & Maple Trees*. https://www.farmandfleet.com/blog/soil-health-maple-trees/

Boyle, R. (n.d.). *Biology of Maple Sap Flow*. College of St. Benedict/ St. John's University. Retrieved April 18, 2024, from https://employees.csbsju.edu/ssaupe/biol327/Lab/maple/maple-sap.htm

Carter, E. (2022). *A Comparative Life Cycle Analysis of The Modern Milkman's Reusable Glass Milk Bottle*. https://studenttheses.uu.nl/handle/20.500.12932/42874

Catanzaro, P., & D'Amato, A. (n.d.). *Forest carbon: An essential natural solution for climate change*. Retrieved April 18, 2024, from https://site.uvm.edu/tdamato/files/2021/03/Catanzaro-and-DAmato-2019-Forest-Carbon.pdf

Checkoway, S.M., 2024. A Simple Model of a Vacuum-Tubing System for Collecting Maple Sap [WWW Document]. University of Michigan. URL https://deepblue.lib.umich.edu/bitstream/handle/2027.42/192661/CSS24-12.pdf?sequence=1&isAllowed=y (accessed 4.21.24).

Clark, J. (n.d.). *How Warm Weather Affects Sap Collection In Maple Trees*. WisContext. Retrieved April 18, 2024, from https://wiscontext.org/how-warm-weather-affects-sap-collection-maple-trees#

Constellation. (n.d.). *Carbon Offsets vs. Carbon Credits*. Retrieved April 18, 2024, from https://www.constellation.com/energy-101/energy-innovation/carbon-credit-vs-carbon-offset.html

Cotnoir, A. (2021). *The End of Maple? Maple Sugaring Amid a Changing Climate*. Audubon Vermont. https://vt.audubon.org/news/end-maple-maple-sugaring-amid-changing-climate

D'Amato, A.W., Kosiba, A.M., Lindgren, C., n.d. Forest Carbon in Your Sugarbush [WWW Document]. UVM. https://www.uvm.edu/extension/agriculture/business/sites/default/files/inline-files/forest-carbon-in-your-sugarbush.pdf (accessed 4.18.24).

D'Amato, T. (n.d.). *Maple forests and carbon*. UVM. Retrieved April 18, 2024, from https://www.uvm.edu/extension/agriculture/business/sites/default/files/resources/D%27Amato%20Sugarbush%20Carbon%202021.pdf

D&B Hoovers. (n.d.) Maple Syrup Industry Participants. [Company Profiles]. Retrieved May 15, 2023 https://app-hoovers-dnb-com.proxy.lib.umich.edu/

Duchesne, L., & Houle, D. (2014). Interannual and spatial variability of maple syrup yield as related to climatic factors. *PeerJ*, *2014*(1). https://doi.org/10.7717/PEERJ.428/SUPP-1

Duchesne, L., Houle, D., Côté, M. A., & Logan, T. (2009). Modelling the effect of climate on maple syrup production in Québec, Canada. *Forest Ecology and Management*, *258*(12), 2683–2689. https://doi.org/10.1016/J.FORECO.2009.09.035

Farrell, M. *Co-Founder*, New Leaf Tree Syrups. Personal Communication. August 15, 2023.

Ferrara, C., & De Feo, G. (2020). Comparative life cycle assessment of alternative systems for wine packaging in Italy. *Journal of Cleaner Production*, *259*, 120888. https://doi.org/10.1016/J.JCLEPRO.2020.120888

Ferrare, K. *Educator*, New York State Maple Producers Association. Personal communication. May 26, 2023.

Flowcarbon. (n.d.). *An Introduction to Carbon Credits*. Retrieved April 18, 2024, from https://www.flowcarbon.com/knowcarbon/an-introduction-to-carbon-credits

Franklin Associates. (2009). *LIFE CYCLE INVENTORY OF THREE SINGLE-SERVING SOFT DRINK CONTAINERS*.

Ghenai, C., 2012. Life cycle assessment of Packaging Materials for Milk and Dairy Products. Int. J. of Thermal & Environmental Engineering 4, 117–128. https://doi.org/10.5383/ijtee.04.02.002

GHG Protocol. (2023). Land Sector and Removals Guidance: Where We Are Now | . https://ghgprotocol.org/blog/land-sector-and-removals-guidance-where-we-are-now

Giesting, K. (2023). *Maple Syrup*. USDA. https://www.climatehubs.usda.gov/sites/default/files/Maple-Syrup_CCRC.pdf

GreenBiz. (2020). *Understanding carbon offsets*. https://www.greenbiz.com/article/quest-carbon-offsets-almost-anything-goes

Gula, L. T. (2023). *Northeast Maple Syrup Season Off to a Very Early Start* . USDA. https://www.nifa.usda.gov/about-nifa/blogs/northeast-maple-syrup-season-very-early-start

Hammonds, T. (2017). *Maintaining a Healthy Sugarbush*. Cornell University. https://smallfarms.cornell.edu/2017/04/healthy-sugarbush/

Hedding, K. *Owner and Operator*, H&H Sugarbush. Personal communication. March 8, 2023.

Helmer, J. (2018). *Climate Change Could Mean Less Maple Syrup For Your Pancakes*. NPR. https://www.npr.org/sections/thesalt/2018/02/12/584528440/climate-change-could-mean-less-maple-syrup-for-your-pancakes

Hoover, C. M., Bagdon, B., & Gagnon, A. (2021). *tandard Estimates of Forest Ecosystem Carbon for Forest Types of the United States*. USDA Forest Service. https://www.fs.usda.gov/nrs/pubs/gtr/gtr_nrs202.pdf

IRS. (2024). *Yearly Average Currency Exchange Rates*. https://www.irs.gov/individuals/international-taxpayers/yearly-average-currency-exchange-rates

ITA. (n.d.). *TradeStats Express-National and State Trade Data*. Retrieved April 18, 2024, from https://www.trade.gov/report/tradestats-express-national-and-state-trade-data

Iyer, R. K., Kelly, J. C., & Elgowainy, A. (2023). Vehicle-cycle and life-cycle analysis of medium-duty and heavy-duty trucks in the United States. *Science of The Total Environment*, *891*, 164093. https://doi.org/10.1016/J.SCITOTENV.2023.164093

Kosiba, AM., 2021. What is Forest Carbon? [WWW Document]. Vermont FPR. URL https://fpr.vermont.gov/sites/fpr/files/Forest_and_Forestry/Climate_Change/Files/WhatIsForestCarbon_Mar2021.pdf (accessed 4.18.24).

Kim, R., & Pierce, B. C. (2018). *Carbon Offsets An Overview for Scientific Societies*. https://www.cis.upenn.edu/~bcpierce/papers/carbon-offsets.pdf

Landi, D., Germani, M., & Marconi, M. (2019). Analyzing the environmental sustainability of glass bottles reuse in an Italian wine consortium. *Procedia CIRP*, *80*, 399–404. https://doi.org/10.1016/J.PROCIR.2019.01.054

Love, N. *Professor of Civil & Environmental Engineering*, University of Michigan. Personal communication. November 17, 2023.

Maguire, T. J., Templer, P. H., Battles, J. J., & Fulweiler, R. W. (2017). Winter climate change and fine root biogenic silica in sugar maple trees (*Acer saccharum*): Implications for silica in the Anthropocene. *Journal of Geophysical Research: Biogeosciences*, *122*(3), 708–715. https://doi.org/10.1002/2016JG003755

Maple From Canada. (2023). *Climate change and maple syrup: how is the industry adapting?* https://www.maplefromcanada.co.uk/news/2023/04/climate-change-maple-syrup-production/#

Maple Syrup Program. (n.d.). *Adapting to Changes in Your Sugarbush*. University of Wisconsin-Madison. Retrieved April 18, 2024, from https://maple.extension.wisc.edu/adaptation-menu/

Massachusetts Maple Producers Association, n.d. Home | Massachusetts Maple Producers Association [WWW Document]. URL https://www.massmaple.org/ (accessed 4.21.24).

Matthews, S. N., & Iverson, L. R. (2017). Managing for delicious ecosystem service under climate change: can United States sugar maple (*Acer saccharum*) syrup production be maintained in a warming climate? *International Journal of Biodiversity Science, Ecosystem Services & Management*, *13*(2), 40–52. https://doi.org/10.1080/21513732.2017.1285815

Miller, B. *Maple Producer*, Vermontville Maple Syrup. Personal communication. May 23, 2023.

Minnesota DNR. (n.d.). *How to Tap and Make Maple Syrup*. Retrieved April 18, 2024, from https://files.dnr.state.mn.us/destinations/state_parks/maplesyrup_how.pdf

Moore, J. D., Duchesne, L., Ouimet, R., & Deschênes, M. Lou. (2020). Liming improves sap characteristics of sugar maple over the long term. *Forest Ecology and Management*, *464*, 118044. https://doi.org/10.1016/J.FORECO.2020.118044

NASS. (n.d.). *Quick Stats database*. USDA. Retrieved April 18, 2024, from https://quickstats.nass.usda.gov/#264E9BD5-D2AF-349C-BBE3-3C5FB57BE132

NASS. (2023). *NORTHEASTERN REGION MAPLE SYRUP REPORT NATIONAL AGRICULTURAL STATISTICS SERVICE*. USDA. https://www.nass.usda.gov/Statistics_by_State/New_England_includes/Publications/Current_News_Release/2023/Northeast-2023-Maple-Syrup-Report.pdf

NASS. (2024). *2022 Census of Agriculture*. USDA. https://www.nass.usda.gov/Publications/AgCensus/2022/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf

National Invasive Species Information Center, n.d-a. Asian Long-Horned Beetle [WWW Document]. USDA. URL https://www.invasivespeciesinfo.gov/terrestrial/invertebrates/asian-long-horned-beetle (accessed 4.21.24a).

National Invasive Species Information Center, n.d-b. Spotted Lanternfly [WWW Document]. USDA. URL https://www.invasivespeciesinfo.gov/terrestrial/invertebrates/spotted-lanternfly (accessed 4.21.24b).

Observatory of Economic Complexity. (n.d.). *Glass Bottles in United States*. Retrieved April 18, 2024, from https://oec.world/en/profile/bilateral-product/glass-bottles/reporter/usa?redirect=true

Pasqualino, J., Meneses, M., & Castells, F. (2011). The carbon footprint and energy consumption of beverage packaging selection and disposal. *Journal of Food Engineering*, *103*(4), 357–365. https://doi.org/10.1016/J.JFOODENG.2010.11.005

Perkins, T. D. (n.d.). *Effects of High Sap Sugar Concentration by Reverse Osmosis on Maple Syrup Attributes*. USDA Natural Resources Conservation Service. Retrieved April 18, 2024, from https://reeis.usda.gov/web/crisprojectpages/0214206-effects-of-high-sap-sugar-concentration-by-reverse-osmosis-on-maple-syrup-attributes.html#

PRé Consultants. (2021). SimaPro (Version 9.3.0) [Computer Software]. PRé Consultants.

Rapp, J. M., Lutz, D. A., Huish, R. D., Dufour, B., Ahmed, S., Morelli, T. L., & Stinson, K. A. (2019). Finding the sweet spot: Shifting optimal climate for maple syrup production in North America. *Forest Ecology and Management*, *448*, 187–197. https://doi.org/10.1016/J.FORECO.2019.05.045

Rechlin, M. *Research Professor*, Appalachian Program. Personal communication. May 17, 2023.
Reinmann, A. B., Susser, J. R., Demaria, E. M. C., & Templer, P. H. (2019). Declines in northern forest tree growth following snowpack decline and soil freezing. *Global Change Biology*, *25*(2), 420–430. https://doi.org/10.1111/GCB.14420
Republic Services. (2023). *Republic Services Polymer Center Opens, Promoting Bottle-to-Bottle Plastics Circularity*. https://media.republicservices.com/2023-12-05-Republic-Services-Polymer-Center-Opens,-Promoting-Bottle-to-Bottle-Plastics-Circularity
RGGI. (2024a). *About the Regional Greenhouse Gas Initiative*. https://www.rggi.org/sites/default/files/Uploads/Fact%20Sheets/RGGI_101_Factsheet.pdf
RGGI. (2024b). *What is RGGI?* https://www.rggi.org/sites/default/files/Uploads/Fact%20Sheets/RGGI_Intro_Factsheet.pdf
Rhone, A., & Ploeg, M. V. (2019). *U.S. Shoppers' Access to Multiple Food Stores Varies by Region*. USDA ERS. https://www.ers.usda.gov/amber-waves/2019/june/u-s-shoppers-access-to-multiple-food-stores-varies-by-region/
Roth. (2019). *How Real Vermont Maple Syrup Is Made | Regional Eats*. YouTube. https://www.youtube.com/watch?v=NV0RrD7ZE4Q
Roth Sugar Bush. (n.d.). *Tubing & Mainline*. Retrieved April 18, 2024, from https://www.rothsugarbush.com/product-category/supply-store/tubing-amp-mainline/
Sanford, S. (2003). *Maple Syrup Energy Use Survey Summary*. University of Wisconsin. https://fyi.extension.wisc.edu/energy/files/2016/05/MapleSyrupEnergyUseSurveySummary.pdf
Science Based Target. (2023). *FOREST, LAND AND AGRICULTURE SCIENCE- BASED TARGET-SETTING GUIDANCE*. https://sciencebasedtargets.org/resources/files/SBTiFLAGGuidance.pdf
Slele Prism. (n.d.). *Protector's Activity: Watch For Invasive Pests That Threaten Maple Syrup Production*. Retrieved April 18, 2024, from https://www.sleloinvasives.org/protectors-activity-watch-for-invasive-pests-that-threaten-maple-production/#
Snyder, S. A., Kilgore, M. A., Emery, M. R., & Schmitz, M. (2019). Maple Syrup Producers of the Lake States, USA: Attitudes Towards and Adaptation to Social, Ecological, and Climate Conditions. *Environmental Management*, *63*(2), 185–199. https://doi.org/10.1007/S00267-018-1121-7/METRICS
StatCan. (2022). *Production and value of maple products*. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210035401
Statista. (2023a). *Maple syrup industry*. https://www.statista.com/study/25140/maple-syrup-industry-statista-dossier/
Statista. (2023b). *U.S. maple syrup production by state 2023*. https://www.statista.com/statistics/372013/us-maple-syrup-production-by-state/#
Stefanini, R., Borghesi, G., Ronzano, A., & Vignali, G. (2021). Plastic or glass: a new environmental assessment with a marine litter indicator for the comparison of

pasteurized milk bottles. *International Journal of Life Cycle Assessment*,*26*(4), 767–784. https://doi.org/10.1007/S11367-020-01804-X/FIGURES/9
Tapper, E. (2019). *Into The Woods: Sugar Maple v. Red Maple – The Hinesburg Record*. Hinesburg Record. https://hinesburgrecord.org/outdoors/into-the-woods-sugar-maple-v-red-maple/#
Technavio. (2020). Global Maple Syrup Market 2021-2025. Retrieved May 18, 2023, from https://insights-technavio-com.libproxy.bus.umich.edu/index.php?route=product/product&product_id=217060
Tierney, G. L., Fahey, T. J., Groffman, P. M., Hardy, J. P., Fitzhugh, R. D., & Driscoll, C. T. (2001). Soil freezing alters fine root dynamics in a northern hardwood forest. *Biogeochemistry*, *56*(2), 175–190. https://doi.org/10.1023/A:1013072519889/METRICS
Trētap (n.d.). - Organic Sparkling Tree Water Made in Vermont. Retrieved April 22, 2024, from https://www.tretap.com/
UN Comtrade Database. (n.d.). *Free access to detailed global trade data*. Retrieved April 18, 2024, from https://comtradeplus.un.org/
United States Census Bureau. (2023). *State Population Totals and Components of Change: 2020-2023*. https://www.census.gov/data/tables/time-series/demo/popest/2020s-state-total.html#v2023
USDA Forest Service. (n.d.). *sugar maple (Acer saccharum) - Climate Change Atlas*. USDA. Retrieved April 18, 2024, from https://www.fs.usda.gov/nrs/atlas/tree/v3/318
US EIA. (n.d.). *Energy units basics*. Retrieved April 19, 2024, from https://www.eia.gov/kids/what-is-energy/energy-units-basics.php
US EPA. (2023a). https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle
US EPA. (2023b). *Glass: Material-Specific Data*. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/glass-material-specific-data
US EPA. (2024a). *Waste Reduction Model (WARM)*. https://www.epa.gov/warm
US EPA. (2024b). *Plastics: Material-Specific Data*. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data
US EPA. (2024c). *Lifecycle Greenhouse Gas Results*. https://www.epa.gov/fuels-registration-reporting-and-compliance-help/lifecycle-greenhouse-gas-results (accessed 4.22.24).
UVM. (2022). *History of Maple - Maple Research Guide*. https://researchguides.uvm.edu/c.php?g=290518&p=1936100
Vermont Evaporator Company. (2020). *The Science of Maple Tree Sap*. https://vermontevaporator.com/maple-school-why-does-sap-run-science/
Weaver, N. J., Wilkin, G. S., Morison, K. R., & Watson, M. J. (2020). Minimizing the energy requirements for the production of maple syrup. *Journal of Food Engineering*, *273*, 109823. https://doi.org/10.1016/J.JFOODENG.2019.109823
Wild, A. *Specialist*, Cornell Maple Program. Personal communication. December 19, 2023.
Wilmot, T. R., Brett, P. W., & Tyree, M. T. (1995). Vigor and Nutrition vs. Sap Sugar Concentration in Sugar Maples. *Northern Journal of Applied Forestry*, *12*(4), 156–162. https://doi.org/10.1093/