Carbon dynamics in maple sugarbushes: measurement, policy, and best practices

By

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Abstract

The maple syrup industry is positioned at the intersection of agriculture and forestry, with an opportunity to use maple forest resources as a carbon-sequestering Natural Climate Solution. Many syrup producers are interested in contributing to climate change mitigation efforts by sustainably managing their forest resources in addition to producing syrup. Previous research employing life cycle assessment of the syrup production process has resulted in guidance for decision-makers on reducing GHG emissions. However, syrup producers are often lacking information and methods to properly account for carbon sequestration in maple sugarbushes. This work provides insights on carbon-conscious sugarbush management by reviewing the factors influencing the carbon dynamics of sugar maple-dominant forests, evaluating how current carbon policy applies to the industry, and presenting measurement and modeling options. Our management recommendations enable producers to better measure and manage their forest resources for carbon sequestration as well as for syrup production.

Keywords: maple syrup, carbon sequestration, GHG emissions, forest carbon, natural climate solutions, agroforestry

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Introduction

Climate impacts of maple syrup production: sources and sinks

Addressing climate change has become an increasingly urgent global priority, driving interest in forest management techniques as a mitigation strategy. The forests of the United States and Canada have historically been managed for various uses, ranging from harvesting for wood products to recreation and agriculture. The maple syrup industry is positioned at a unique intersection between agriculture and forestry with opportunities for climate-smart management of its forest resources. The agricultural sector remains a significant source of greenhouse gas emissions, accounting for 10.5% of total U.S. emissions in 2022 (EPA, 2024). Many syrup producers are interested in how they can contribute to climate change mitigation efforts, which requires consideration of both the syrup production process and the forestry component of a maple syrup operation.

To characterize the environmental impact of the maple syrup industry, Checkoway et al. (2024) developed a life cycle assessment model for syrup production. They quantified energy consumption of the syrup production process and estimated the carbon emissions across producer archetypes defined by production scale and processing technology. This research offers insight into variability among operations, energy use in specific stages of syrup production, and strategies for emissions reduction. However, carbon dynamics of maple forests were not incorporated in the recommendations, and the lack of information on this topic continues to limit understanding of the complete carbon balance of maple syrup production. This paper integrates science and policy to provide new insights for managing forest carbon in the maple syrup industry. It aims to guide syrup producers interested in the forest ecology, management actions, and policy related to carbon in maple forests and inform researchers of areas where future work is most needed to support the industry in reaching its climate goals.

Carbon sequestration as a natural climate solution

Carbon sequestration is defined by the Intergovernmental Panel on Climate Change (IPCC) as the process of storing carbon in a pool, which can occur through natural or man-made processes (*Glossary — Global Warming of 1.5 ºC*, n.d.). Carbon sinks are those pools that actively remove carbon dioxide from the atmosphere and store more carbon than they release. Forests serve as an important carbon sink, with stored carbon increasing over time through CO_2 uptake during tree growth. Studies of carbon storage in northern hardwood and red pine forests of the Great Lakes region have shown that northern hardwood stands typically accumulate more carbon in living biomass than pine stands, making maple forests a particularly significant regional carbon stock warranting preservation (Gahagan et al., 2015). Climate-conscious management of northern hardwood forests requires optimizing carbon sequestration benefits while meeting requirements for activities of economic and cultural significance, like maple syrup production.

The concept of “Natural Climate Solutions” provides insight into the environmental benefits interwoven with forest-based industries like maple syrup production. Natural Climate Solutions (NCS) are actions that restore, protect, or improve the management of nature to mitigate climate change by reducing greenhouse gas emissions and storing carbon (Griscom et al., 2017). NCS are widely recognized for their importance in climate change mitigation,

and the IPCC has designated the increased implementation of NCS as essential for reaching climate change mitigation goals (Ellis et al., 2024). In the original definitions of NCS pathways developed by Griscom et al., over two-thirds of the cost-effective opportunities were found to be forest-based solutions. Forest NCS encompass practices focused on both the increase in forested land and the protection and management of existing forests and can include industries like recreation, wood products, and syrup production that preserve the environmental benefits of forests while providing economic value. However, to claim an industry's contributions, it is important to thoroughly understand its carbon dynamics and avoid unverified or overstated claims.

Carbon management challenges for the maple industry

A notable feature of the maple syrup industry is the heterogeneity in both syrup production methods and in characteristics of maple sugarbushes. Recent research on the production process found variation from small family-run operations using bucket sap collection and wood-fired evaporators to commercial-scale operations with modern technology like vacuum tubing systems and reverse osmosis (Checkoway et al., 2024). This variation leads to significant differences in carbon and energy footprints, with the overall emissions range of 3.5 - 118 kg CO_2e per gallon of syrup, depending on the scale and efficiency of the production operation.

Sugarbushes also have highly variable characteristics. The syrup industry spans primarily southern Ontario, Quebec, and New Brunswick as well as the northeastern and north-central region of the U.S., a geography over which there is significant variation in forest type (Perkins et al., 2022). Sugar maple (*Acer saccharum*), red maple (*Acer rubrum*), and black maple (*Acer nigrum*) are the primary species used for sugaring, though sugarbushes are composed of a variety of other species, commonly including American beech (*Fagus grandifolia*), American basswood (*Tilia americana*), yellow birch (*Betula alleghaniensis*), black cherry (*Prunus serotina*), northern red oak (*Quercus rubra*), tulip tree (*Liriodendron tulipifera*), and black walnut (*Juglans nigra*) (Perkins et al., 2022). Assessment of syrup production potential in maple-dominant hardwood forests across the range of the industry found that species composition, forest age, and forest density are quite variable (Farrell, 2013a). Management practices also vary widely among producers. For example, traditional stocking recommendations range from 25 to over 100 trees per acre (C. Smith & Gibbs, 1970). Some sugarbushes are highly managed while others are left in a more natural or minimally managed state.

Despite this variability, the maple syrup industry is becoming increasingly motivated to understand the carbon dynamics of sugarbushes. For some, these pursuits are motivated mainly by a desire to contribute to climate change mitigation efforts. Others may be more motivated by a desire to make green marketing claims, participate in carbon markets, or promote growth of the industry. To inform producers interested in gaining a better understanding of carbon management, this paper reviews the key factors influencing carbon sequestration of a sugarbush, applicable carbon policy and standards, and methods for measuring and modeling forest carbon sequestration. Literature on these subjects specific to the maple industry is limited, but insights from policy and other forest management approaches can be applied to the operational characteristics of the maple industry to inform climate-smart management and future research opportunities.

Factors influencing carbon dynamics in the maple sugarbush

Maple sugarbush forests are continuously changing ecosystems composed of multiple carbon pools and fluxes. Forest carbon sequestration is the net removal of carbon dioxide from the atmosphere, accounting for the uptake through photosynthesis and the release from respiration. This leads to a positive net change in the carbon stored in the vegetation, detritus, and biomass pools, which depends on the biomass accumulation during growth and decomposition processes (Lorenz & Lal, 2010). To understand the patterns in forest growth and biomass accumulation, it is necessary to consider key influences, which can be organized into environmental factors, forest stand characteristics, and disturbances (Figure 1). Understanding and grouping the factors that affect the carbon dynamics of the maple sugarbush provides insights about which factors can be influenced by management action with the goal of increasing sequestration to mitigate climate change.

Environmental factors

The large geographic range of sugar maple and the presence of the sugaring industry throughout multiple states and Canadian provinces means that maple sugarbushes experience significant variance in environmental conditions and effects from climate change. Forest growth, the key driver of biomass accumulation, depends on climate, soil, and topography.

Climate

Climate conditions significantly impact forest growth, especially temperature and precipitation. Previous large-scale studies of northern hemisphere forests demonstrated that temperature elevation extending the growing season can increase photosynthesis and therefore promote greater accumulation of forest biomass, but can also increase decomposition rates, leading to greater release of CO_2 (Myneni et al., 1997). Additionally, long-term temperature increases due to climate change have led to concern for maple forests. Climate change-induced thaw-freeze events, in which a refreeze follows an early initial spring thaw, have led to abrupt and significant growth declines for sugar maple trees (Moreau et al., 2020).

Precipitation also influences tree growth because soil moisture is critical for nutrient uptake and photosynthesis. Sugar maples typically grow in regions with moderate to high rainfall, and drought poses a challenge for the species' vigor. Evaluation of varying durations of drought on *Acer saccharum* found significantly reduced chlorophyll with the effect magnified by longer drought time (Mulozi et al., 2023). This indicates negative impacts on photosynthesis and thus reduced biomass accumulation. Additionally, there is evidence of long-lasting growth declines in sugar maple forests for years following droughts (Nolet & Kneeshaw, 2018). Sugar maple ecotypes from the southwest of the species' range in the U.S. have greater drought tolerance due to their comparatively better water use efficiency (Hauer et al., 2021). However, the species is considered drought susceptible, so there is concern about the impacts of climate change and the potential of combined effects of increasing temperature, thaw-freeze events, and drought on sugar maple forests. The effects on the species' growth due to these climate variations indicate that inter-annual variation in carbon sequestration should be expected, so understanding the carbon dynamics of a sugarbush requires regular repeated measurements.

Soil

Soil structure and composition also influence carbon sequestration. Macroaggregates and microaggregates, soil particles greater than and less than 250 μm, respectively, work together to support the accumulation of soil organic carbon (SOC). Macroaggregates physically protect organic matter from rapid decomposition that releases carbon into the atmosphere at comparatively high rates, while microaggregates, such as clay and silt, stabilize SOC stocks over long time periods (Verchot et al., 2011). The nutrient and mineral composition of forest soils also play an important role in carbon sequestration. Nitrogen is known to be the primary limiting nutrient in northern hardwood forests, with phosphorus also sometimes taking on a limiting role in forest stands with high nitrogen soils (Zukswert et al., 2025). Growth rates of aboveground biomass in sugar maple forests can vary depending on the availability of these nutrients. The presence of iron and aluminum oxides is also known to increase SOC in northern hardwood forests due to these minerals' ability to bind to organic matter (Wagai et al., 2020; Zhao et al., 2016). In contrast, sandy soils with lower clay, iron, and aluminum oxide content are more prone to carbon loss, which is supported by a study of sugar maple health in which plots experiencing growth declines were found to be more likely to have sandier, less acidic soils (Minorsky, 2003). In addition to the physical structure and mineral content, the transformation of litter into the SOC pool also depends on microbial activity and acidity. Northern hardwood forests have more acidic soils than other forest types, and this is known to slow decomposition rates, which allows for greater SOC accumulation and reduced CO_2 emission to the atmosphere (Bélanger et al., 2021).

Forest stand characteristics

Forest carbon sequestration is significantly influenced by the characteristics of the vegetation within a stand. Tree age, age composition, forest density, and species composition all affect growth patterns and biomass accumulation.

Forest age

It is well known that growth over a tree's lifetime is non-linear, with the highest rate of biomass increase typically occurring when a young tree is transitioning to maturity. This growth trend means that at the stand level, age has a clear impact on Net Primary Productivity (NPP) of forests. Evaluation of global forest types found that temperate forest stands have their highest NPP during the intermediate age period of 30-120 years (Pregitzer & Euskirchen, 2004). Examination of this trend specifically for maple dominant forest stands found that maple/beech/birch and alder/maple compositions experience peak NPP between 20 and 40 years, and then decline gradually (He et al., 2012). Decreasing NPP represents a reduced rate of biomass accumulation, so annual carbon sequestration slows as the trees age beyond this peak. Past evaluation of the carbon effects of forest conversion opposes claims that young forest maintained through harvesting has optimal climate benefits (Harmon et al., 1990). Though the rate of carbon accumulation slows as trees age, old-growth forests have been found to have centuries of carbon sequestration ability and act as large carbon sinks vital for climate change mitigation (Luyssaert et al., 2008). The advantages of maximized NPP and long-term carbon storage can be pursued through management for mixed-age northern hardwood stands.

Forest density

Forest density plays an important role in carbon sequestration because higher density forests typically have greater aboveground carbon stocks, but high density can also limit growth and forest succession. USDA research studied sugarbush stocking, with the goal of allowing all tapped trees sufficient space to grow a full crown (C. Smith & Gibbs, 1970). This work produced recommendations for both basal area and number of individuals based on the average diameter at breast height (DBH) class of the stand, but did not consider carbon. More recent experimental management treatments have demonstrated increased carbon storage with increased density for northern hardwood forests. Treatments designed to increase density by encouraging structural complexity in Vermont hardwood-conifer forests resulted in greater carbon storage after 10 years than other treatments (Ford & Keeton, 2017). Assessment of hardwood forest in New Hampshire over seven decades similarly found that forest stands with greater density have greater carbon storage (Hoover, 2011). Future work is needed to better understand the ideal sugarbush densities, but forest managers aiming to increase carbon storage and sequestration should consider management actions that increase forest density, especially through increased complexity and understory companion species, while being mindful of the stocking limits that allow sugar maples to grow a full crown.

Species composition

Another influence related to density is the species composition within a forest stand. The species present in a forest impact the growth patterns and existence of understory layers, influencing the amount and rate of carbon sequestration. Maple sugarbushes are composed of a variety of tree and plant species beyond maples, and other species can vary significantly among sugarbushes.

Species besides maples can impact a forest's soil carbon and stress tolerance. Certain tree species – including eastern hemlock (*Tsuga canadensis*), white birch (*Betula papyrifera*), and black cherry (*Prunus serotina*) – develop root systems that promote soil aggregation and greater SOC storage (Chen et al., 2025). A study of sugar maple forest at the northern part of its range found that soil respiration – the release of CO_2 from the soil – is highest in stands with balsam fir (*Abies balsamea*), moderate in stands with yellow birch (*Betula alleghaniensis*), and lowest in stands with American beech (*Fagus grandifolia*) (Bélanger et al., 2021). Though soil respiration alone does not determine the overall trend in carbon storage in a forest, these findings demonstrate that companion species influence soil carbon storage in sugar maple forests. In addition to specific companion tree species, promotion of understory development and diversity is a management strategy recommended for enhancing forest carbon sequestration (Ontl et al., 2020). Management to encourage understory growth and fast-growing species can promote annual carbon sequestration, while encouragement of long-lived hardwood companion species, like those mentioned above, can increase the overall carbon storage of a sugarbush.

Disturbances

Forest managers seeking to promote carbon sequestration care about the longevity of the carbon stock, which depends on the ongoing health of the forest. Forests can experience factors causing a reduction or halting of carbon sequestration or even the release of much of the forest's stored carbon.

Disease

Since forest carbon sequestration depends on growth, diseases that reduce growth or lead to mortality can have a significant impact. Armillaria Root Rot, caused by *Armillaria mellaea* fungus, has long been observed to affect sugar maple trees, resulting in foliage yellowing, root decay, branch death, and potential mortality (Leapheart, 1963). Leaf blotch and spot diseases are also well known to affect sugar maples, and fungal pathogens commonly causing these conditions include *Gloeosporium apocryptum* and *Phyllosticta minima* (Olson, n.d.). Sapstreak disease, caused by the fungus *Ceratocystis virescens* invading roots and stem bases through wounds, has been a particular concern in sugarbushes (Houston, 1993). Though sugar maples can survive these fungal infections, the resulting defoliation slows tree growth, and ongoing infection can lead to mortality. Since the 1990s, there have been multiple studies noting instances of sugar maple growth declines due to the combined effects of disease, invasive species, and environmental factors, but more research is needed to draw conclusions about future implications for the overall species (Hall et al., 1998; Minorsky, 2003; Bishop et al., 2015).

Disease can also impact carbon dynamics in a sugarbush by affecting the companion species and causing changes to succession patterns. Beech bark disease effects the American beech (*Fagus grandifolia*), causing fatality of mature individuals. This has been shown to effect forest succession patterns by leading to an increased number of beech saplings, which indirectly reduces the survival of sugar maple saplings due to shading (Hane, 2003). Harvesting of beech saplings has been identified as a potential silvicultural method to support sugar maple regeneration, but optimal harvesting intensity remains unclear (Leduc et al., 2024).

Invasive species

Invasive species stress the health of sugarbushes through mortality or reduced growth. Defoliating insects can destroy significant portions of a tree's crown, leading to reduced photosynthesis. Forest tent caterpillar (*Malacosoma disstria*) and elm spanworm (*Ennomos subsignaria*) outbreaks have caused widespread defoliation and mortality in sugar maple stands (Hall et al., 1998). Furthermore, defoliation from the forest tent caterpillar was found to weaken sugar maple in combination with climate events like thaw-freeze cycles (Moreau et al., 2020). Maple forests can also be affected by invasive species targeting non-maple companion trees. Ash trees are commonly found alongside sugar maples, and widespread mortality due to the emerald ash borer (*Agrilus planipennis*) influences forest succession and promotes the establishment of invasive plant species (Klooster et al., 2018).

Some concern has been raised about the effect heavy deer herbivory has on forest regeneration. Sugar maple forest in many regions overlaps with high deer populations, and herbivory of seedlings can affect some tree species' ability to reach maturity. Evaluation of this phenomenon over 17 years in northern Michigan found that Eastern hemlock (*Tsuga canadensis* L.) and yellow birch (*Betula alleghaniensis* Britton) were prevented from reaching heights greater than a meter, while sugar maple and ironwood (*Ostrya virginiana* Mill.) were able to successfully grow into saplings in spite of deer herbivory (VanderMolen & Webster, 2021). Another recent experiment corroborated the finding that deer herbivory is likely not preventing the maturity of sugar maples (Jones et al., 2023). High concentrations of deer have been hypothesized to limit regeneration of a variety of species, with anecdotal

reports of this being true for sugar maple in some locations (Beguin et al., 2009). Whether deer herbivory is specifically preventing regeneration of sugar maple in a given forest, it is clear that high levels of herbivory can impact multiple species and effect the growth, composition, and understory of sugar maple-dominant forests.

Concerns have also been raised about the effects of invasive understory plants – such as honeysuckle, barberry, buckthorn, and garlic mustard – on sugar maple forest. Recent research found that the presence of honeysuckle (*Lonicera maackii*) was correlated with reduced sugar maple seedling recruitment, though the transition from seedling to sapling was positively affected, and sapling to tree was unaffected (Cameron & Culley, 2016). More research is needed to reach clear conclusions about the long-term effects of honeysuckle and other invasive species, but their presence warrants consideration and management action to prevent overgrowth in sugarbushes where these species are present.

Pollution

Anthropogenic environmental contamination, including air pollutants and agricultural runoff, has an impact on northern hardwood forest health and growth. Sugar maple growth can be limited by acid deposition, but since 1990, when emissions regulations in the Clean Air Act became stricter, acid deposition has been reduced (Stern et al., 2023; Talhelm et al., 2012). Some anthropogenic nitrogen deposition has been found to improve sugar maple growth in areas limited by dry conditions (Ibáñez et al., 2018). However, chronically elevated nitrogen levels, now found in many northern hardwood forests, may cause nutrient imbalances suboptimal for sugar maple growth (Bethers et al., 2009). Though none of these pollutants have been detrimental to the species, they should be considered potential factors limiting growth in sugarbushes bordering industrial areas, highways, or areas with significant agricultural runoff.

Fire

Some sugar maple forests, particularly those in the northern part of the species' range, show evidence of historical fire influence. Evaluation of fire evidence from charcoal in soil layers in Québec sugar maple forests determined a mean fire interval of 250 years (Pilon & Payette, 2015). Consideration of sugar maple successional patterns in the same northern region found that the species developed dominance after fire (Nolet et al., 2008; Payette et al., 2018). Recent evaluation of fire presence in the lower part of the sugar maple range, from the Great Lakes to the northeast, has found that fire is least frequent in northern hardwood forests (Frelich et al., 2021). Despite low fire frequency in this forest type, the drastic changes fire causes in forest carbon warrant consideration by managers of sugar maple forests, especially if climate change alters current fire patterns.

All the influences shown in Figure 1 impact carbon sequestration through their effect on biomass accumulation from forest growth. The geographic variation of these influences indicates that two sugarbushes in different locations cannot be assumed to have the same carbon sequestration rate. Additionally, due to the presence of temporally varying influences and the potential for drastic changes from mortality-inducing events, a given sugarbush cannot be assumed to maintain constant carbon sequestration from year to year.

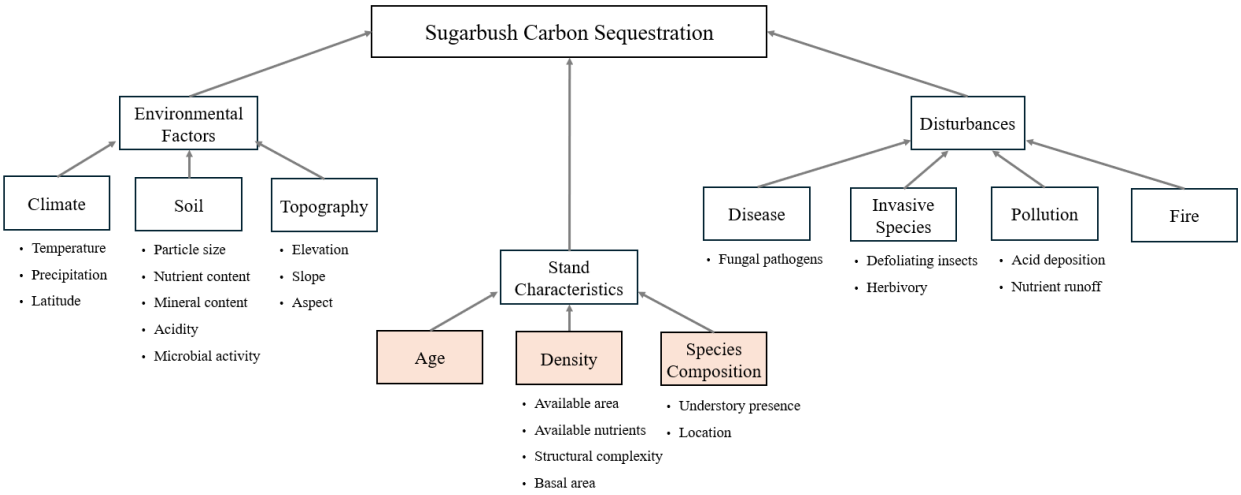


Figure 1: Influences on sugarbush carbon sequestration

Considering the temporal variation of the influential factors in Figure 1, it is evident that their variation occurs on different time scales. This raises the question of which can be influenced by human actions within the timescale of sugaring operations. Environmental factors are more site-specific and can be expected to change only on a long time scale, whereas disturbances occur suddenly and often due to forces external to a given sugarbush. The variation of the stand characteristics can be expected to occur on a moderate timescale, making these factors, highlighted in orange, the most suitable for the focus of management interventions seeking to impact carbon sequestration.

The variation between and within sugarbushes means that measurement and modeling strategies are important for achieving a reliable understanding of carbon dynamics as a basis for management decisions. Forest management of stand characteristics is also strongly influenced by environmental policy in addition to the ecological factors discussed.

Carbon policy and standards applied to the maple sugarbush

The modern landscape of environmental policy and standards, ranging from legal requirements to voluntary carbon markets, contains restrictions as well as opportunities for the maple industry. Industry members are interested in environmental marketing and carbon credits. This space has evolved significantly in recent years, and a thorough understanding of current best practices is important for the industry.

Legal requirements

Adhering to the applicable environmental laws of the United States or Canada is foundational to the carbon management of a maple sugarbush. Relevant laws include broadly applicable environmental regulations that affect forest management and legal standards for environmental marketing. The Clean Water Act can apply to sugarbush infrastructure, particularly for properties that contain wetlands or rivers, and the Endangered Species Act can affect forest management in areas that overlap with endangered species habitat (Endangered Species Act, 1973; Federal Water Pollution Control Act, 1972).

Environmental marketing regulations from the U.S. and Canada are relevant to carbon management decisions that involve presenting environmental claims to the public. As public interest grows, many industries have become increasingly motivated to communicate their sustainability progress through marketing claims. In the United States, Section 5 of the Federal Trade Commission (FTC) Act prohibits deceptive acts and practices in commerce (Federal Trade Commission Act, 1914). To aid interpretation in the context of green marketing, the FTC developed its Guides for the Use of Environmental Marketing Claims, or "Green Guides," which cover a wide range of claims, with the most relevant for sugarbush management being the sections on general claims and carbon offsets. For general environmental benefit claims, the guidance directs marketers to use clear qualifying language to describe specific environmental benefits and to avoid statements that are technically true but lead the consumer to overestimate the product or service's environmental benefits (Federal Trade Commission, 2012). For the case of carbon offsets, the guide states that claims must be quantified by reliable scientific accounting methods and must go beyond what is required by law (Federal Trade Commission, 2012). Additionally, marketers are directed to be transparent about whether there are trade-offs between the environmental benefits being advertised and related environmental downsides.

Similarly, the Competition Bureau of Canada has an Environmentally-Related Claims policy, which was updated in June of 2025 to introduce more robust requirements for businesses to justify their environmental claims. The policy prohibits false or misleading claims, exaggeration, and vagueness and requires environmental claims to be based on substantiation developed in accordance with internationally recognized methods (Competition Act, 1986). The accompanying guidance explains that recognition of a method can come from a variety of sources, such as standards-setting bodies, regulatory authorities, and industries, and that international recognition requires recognition in two or more countries, though not necessarily by the governments of those countries (Competition Bureau Canada, 2025). For those entering the green marketing space, these government guidelines for complying with legal requirements are a basis for making ethical claims about forest carbon management. However, they are a minimum basis, not a standard for excellence, and there are further resources to consider.

Compliance standards

Compliance standards form another area of the environmental regulatory space applicable to forest carbon projects. The maple syrup industry is not directly governed by compliance standards, since this category of environmental regulation is targeted at sectors subject to mandatory caps on their greenhouse gas emissions (USDA, 2023). However, forest landowners may still be eligible to generate offset credits by voluntarily participating under these protocols. Additionally, the standards provide thorough documentation of current policy on greenhouse gas removals and carbon management and overlap with voluntary carbon markets. Even outside the carbon markets, the frameworks in these standards can provide information for those seeking to better understand carbon accounting best practices and long-term forest management.

Voluntary carbon markets

Voluntary carbon markets emerged in the 1990s in a state of limited regulation and received significant criticism for the unreliability of offsets and double counting. Over the past two decades, they have been promoted by the increase in net-zero targets following the Paris Agreement in 2015 and have been forced to increase their rigor of standards and verification (Kreibich, 2024). Despite ongoing criticism and the likelihood of continued changes, the voluntary carbon markets have an impactful presence in current carbon management and can provide insights for best practices.

Forestry projects have been a long-term component of voluntary carbon markets, and they fall into four main categories: reforestation, afforestation, avoided deforestation, and improved forest management (IFM). Reforestation and afforestation are not realistic pathways for the maple industry, given that syrup production relies on mature trees, and planting a maple forest cannot financially or practically compete with existing untapped maple forests (Farrell, 2013b). In global carbon markets, avoided deforestation projects are most common in areas with high deforestation pressure, particularly tropical regions participating in the UN REDD+ initiative, while IFM projects are heavily focused in the United States (Gallemore et al., 2025). Analysis of the U.S. carbon markets found that from 2013-2022, 93% of forestry carbon credits issued came from IFM projects (USDA, 2023). This leaves IFM as the category that is most practical and regionally appropriate for the maple industry. However, it is important to note that IFM projects have received significant criticism for over-crediting and some view them as a lower quality credits (Haya et al., 2023; Schneider et al., 2024). Some of the current standards for IFM projects will be reviewed to determine best practices applicable to the maple industry.

Sources of Guidance

Standards organizations and NGOs have played a significant role in developing best practice frameworks that have guided forest carbon management and voluntary carbon markets. The International Organization for Standardization (ISO) has published standards for greenhouse gas accounting at the project and product levels (International Organization for Standardization, 2018; International Organization for Standardization, 2019). These standards provide a foundation for best practices in various sectors and types of greenhouse gas accounting.

A few organizations have set the standard for what is currently considered high integrity carbon accounting in forestry and agricultural projects. The 2006 guidelines on greenhouse gas inventories from the IPCC recognized Agriculture, Forestry, and Other Land Use (AFOLU) as a significant sector warranting unique accounting methods (Simon Eggelston et al., 2006). In recent years, more specific guidance on forest carbon management has been developed from other sources. The Science Based Targets Initiative and the World Resources Institute have jointly produced guidance on GHG accounting specifically tailored to the forestry, land use, and agriculture (FLAG) sector. The Forest, Land, and Agriculture Science-Based Target-Setting Guidance outlines requirements for companies to align with the Paris Agreement, though it is targeted at FLAG industries with higher emissions than the maple syrup industry (Anderson et al., 2023). However, the guidance includes broadly applicable recommendations for setting emission and removal targets, making no-deforestation commitments, and conducting separate accounting of land sector and industrial emissions (Anderson et al., 2023). The GHG Protocol Land Sector and Removals Guidance, currently in development, provides a more general and comprehensive rulebook for quantifying, reporting, and managing GHG emissions from land sector activities of any organization (GHG Protocol Land Sector and Removals Guidance, 2022). The Integrity Council for the Voluntary Carbon Market, a nonprofit founded with the goal of guiding voluntary carbon reporting, has applied best practices for GHG management in the development of its guidance specifically for carbon credits. Their recently released Core Carbon Principles provide straightforward criteria for identifying high-quality carbon credits (Core Carbon Principles Assessment Framework and Procedure, 2024).

The above sources of guidance provide a foundation of best practices for carbon management in land and forest-based industries and inform compliance and voluntary carbon market standards. For producers seeking general guidance about accounting and claims, the GHG Protocol Land Sectors and Removals Guidance is most relevant. For those interested in participating in carbon markets, all these sources provide different important insights for best practices.

Insights from best practices

The standards listed in Table 1 in the Supplementary Information are current examples of widely referenced standards relevant to maple forest management. Whether for compliance or voluntary markets, all the latest versions of these standards require projects to be registered, conduct rigorous assessments, and adhere to reporting and third-party review requirements. The commonalities in the assessment methods show that those interested in developing IFM projects that follow current best practices should prioritize understanding their potential project's baseline, additionality, and permanence.

Determination of a project baseline is a fundamental component of all compliance and VCM standards reviewed. The ISO 14064-2 standard defines a greenhouse gas baseline as the quantity of emissions or removals that would occur in the absence of a project's implementation (International Organization for Standardization, 2019). This definition is followed by all the carbon market standards listed in SI Table 1, though they each present expectations for demonstrating and documenting a baseline. Reviews of baseline setting methods across many projects have found that inaccurate baselines can lead to over-crediting, but more rigorous standards and measurement techniques can combat this (Nolan et al.,

2024). Examples of errors that can skew baselines to promote over-crediting include assuming unrealistically high deforestation rates as the baseline for an avoided deforestation project or assuming lower than actual initial sequestration before implementing an IFM project. Current best practices for setting a baseline include predicting realistic alternative scenarios and conducting site-specific measurement of carbon dynamics before the implementation of a crediting project.

Additionality is a foundational element of voluntary carbon standards. It is commonly understood as a project's ability to cause emissions reductions or removals beyond the baseline scenario. Its definition does vary significantly between sources, with at least 10 different methods being used to demonstrate additionality, leading to concerns about inconsistent and circular logic (Gillenwater, 2012; Valatin, 2011). SI Table 2 shows which of the common criteria for demonstrating additionality are included in each of the seven standards reviewed. The requirement for legal additionality is present in all the standards, and to satisfy it, a project's actions must not already be required by law. Financial additionality is present in three of the standards and requires that the project be less financially viable or appealing without the carbon credit component (The ACR Standard, 2023; VCS Additionality Assessment, 2024). Demonstrating implementation barriers requires that the project face some sort of obstacle to its execution that would be solved by carbon credit revenue, and this form of additionality is required by both the American Carbon Registry Standard and the Verified Carbon Standard (The ACR Standard, 2023; VCS Additionality Assessment, 2024). Demonstrating additionality through a performance standard test is included in five of the seven standards reviewed and requires demonstration that a project's activities are going above and beyond what was previously occurring or is considered business as usual for the industry or location. However, some standards, including the Regional Greenhouse Gas Initiative Forest Offset Protocol and the Canadian Federal Offset Protocol for Improved Forest Management on Private Land, assume that IFM projects automatically fulfill this requirement due to their implementation of specific management activities (Improved Forest Management on Private Land, 2024; Regional Greenhouse Gas Initiative, 2018). The common practice method of demonstrating additionality is present in two of the standards reviewed and requires that a project show its activities are not widespread within its industry or geographic area (The ACR Standard, 2023; VCS Additionality Assessment, 2024). In summary, being able to demonstrate legal additionality and at least one of the other additionality types is essential for a project's eligibility under this set of carbon market standards.

Permanence, meaning a project's ability to generate long-term carbon benefits by keeping carbon out of the atmosphere, is another key element of carbon market standards. SI Table 3 shows how the standards reviewed compare in terms of their permanence criteria. Long-term monitoring is an essential aspect of permanence, and five of the standards reviewed require 100 years of monitoring after the sale of credits. The American Carbon Registry and Verified Carbon Standard both have a shorter minimum monitoring period of 40 years (The ACR Standard, 2023; VCS Additionality Assessment, 2024). All seven standards require the project to assess the risk of credit reversal, which is when some of the carbon benefits of a project are undone. This can come from a project's activities falling short of their predicted carbon benefits, changes in management or land use, or disturbances like forest fires. In cases where reversals occur, projects are required to provide compensation. The most common

strategy, implemented by six of the standards reviewed, is reserving a percentage of the carbon credits (determined based on risk assessment) in a buffer pool for compensation in the case of a reversal. These criteria for permanence require projects to commit to long-term monitoring, and the capability to meet this requirement must be considered by anyone considering entering this space.

To register a project in the voluntary carbon markets, maple forest managers would need to understand and comply with legal regulations, determine their sugarbush's baseline carbon sequestration, develop an improved forest management plan, demonstrate their claim of additionality, execute regular measurement, and adhere to reporting and third-party review requirements. These activities require significant labor and time investments, and those with an interest in participating should be realistic about their capabilities. Small-scale operations, of which the maple industry has many, have been shown to experience barriers due to the cost and complexity of achieving compliance with carbon market standards (Wise et al., 2019). This is partly due to the time and resources required to measure forest carbon sequestration, and options for conducting these measurements are explored in the following section.

Measurement and modeling of carbon sequestration in the maple sugarbush

Measurement techniques

Forest carbon pools

Estimating carbon stored and sequestered in forest ecosystems is an evolving science with different components of the forest system exhibiting distinct carbon accumulation patterns. The division of forest carbon into pools is foundational to standard measurement strategies. Greenhouse gas inventory guidelines from the IPCC present a standard division of the pools as above-ground biomass, below-ground biomass, dead wood, litter, soil carbon, and harvested wood products (Eggleston et al., 2006).

Understanding the distribution of carbon between the pools is useful for measurement but is not consistent between forests. Previous research has examined the distribution of carbon among the pools in forests of specific types and ages. For 80- to 100-year-old northern hardwood forests in New England, an approximate carbon distribution is 40% live above-ground, 31% soil, 16% dead wood, 7% live below-ground, and 6% litter (D'Amato et al., 2024). Carbon distribution is not static and can be impacted by all the factors that impact carbon sequestration, as well as management action. For example, in old hardwood stands that have declined in their rate of carbon sequestration, soil carbon can surpass above-ground biomass as the largest carbon pool (Addo-Danso et al., 2016). Due to these fluctuations, repeatable measurements at the forest stand level for each of the carbon pools are important.

Measuring live aboveground biomass

The measurement options for above-ground biomass are the most well-researched and least challenging to conduct. The standard approach involves field measurements of DBH or total height, conversion to total biomass using species-specific allometric equations, and multiplication by a factor representing the carbon content per unit of biomass (Pearson et al., 2007; Vashum, 2012). This approach depends on previous direct measurements of total biomass, which have been used to generate allometric equations that relate the easily measured variables of DBH and height to total tree biomass for a given species across the United States and Canada (Jenkins et al., 2003; Lambert et al., 2011; Woodall et al., 2010). This is a commonly used technique, but it possesses some drawbacks. Accuracy is reduced when it is applied in regions and stand ages different than where they were developed, and they are known to overestimate biomass when applied to young hardwood stands (Fatemi et al., 2011). Additional error can be introduced from the use of generalized assumptions about the carbon-to-biomass ratio and the sampling methods used when conducting measurements across large forest areas (Vashum, 2012).

Measuring belowground biomass

Belowground biomass, primarily made up of coarse and fine tree roots, is a substantial carbon pool, yet measurement options are limited. Direct measurement requires excavation of coarse roots and coring of fine roots, which is both destructive and infeasible for entire stand or forest-scale measurements (Pearson et al., 2007). The commonly used alternative

option is to rely on the indirect measurement technique of estimating belowground biomass as a function of the aboveground biomass, known as the root-to-shoot ratio (Addo-Danso et al., 2016). Due to the limitations in accuracy of this method, methods should be designed for conservative estimations since underestimating is preferrable when claims about forest carbon sequestration will be made for marketing purposes or the sale of carbon credits .

Measuring necromass

Necromass, composed of dead wood and litter on the forest floor, is more easily accessible for measurement than the below-ground biomass or soil carbon pools using techniques such as fixed-area plots, line-intersect surveys, and decay-class classification (Maas et al., 2020; Russell et al., 2015). These methods are well established, with the most suitable strategy depending on the needs for a given project. The main challenges in the measurement of necromass are inconsistency in sampling protocols and terminology across studies, which can lead to lack of clarity or difficulty comparing results (Maas et al., 2020). Detailed and transparent reporting of methods is particularly important when conducting measurements of this pool.

Measuring soil carbon

Soil carbon is sometimes neglected in measurement, but it is one of the largest pools in northern hardwood forests and is more stable than above-ground biomass, which is more affected by a variety of disturbances. The standard process for measuring soil carbon involves extracting soil cores for laboratory analysis using either dry combustion or wet oxidation to determine their organic carbon content (Eggleston et al., 2006). The results are then extended to determine soil carbon content per area of forest. These laboratory techniques are well supported by literature, but challenges include labor and cost as well as the need to design sampling to capture variation across soil type and topography.

Standard estimations by forest type

Due to measurement being resource intensive and time consuming, standard estimates of carbon storage by forest type are valuable for informing management decisions. Studies conducted by the United States Forest Service have determined yield tables of carbon pools as a function of stand age for 51 forest types, and similar information has been developed for Canadian forests (Lambert et al., 2011; J. Smith et al., 2006). This information is valuable for gaining overall understanding of the carbon dynamics of different forest types, but it is generalized and cannot replace measurement of specific sites for management decisions that depend on stand-level variation.

Modeling options

Modeling approaches provide management value by extending the insights of field measurement. Forest carbon models contribute to GHG mitigation efforts by enabling estimation of carbon across broad areas and allowing for prediction of management and disturbance scenarios (Dye et al., 2024; Woodall et al., 2025).

Evaluating existing modeling techniques for their applicability to a maple sugarbush requires the consideration of spatial scale, temporal scale, target carbon pools, and accessibility for use. Carbon modeling can range from analysis of individual trees to models of entire countries or regions. Data on the areas of currently operating maple sugarbushes is limited,

but a survey of Vermont syrup producers found that the median property size is 75 acres (Isselhardt et al., 2022). The forest stand level is the most appropriate spatial scale to model maple sugarbushes, which means that models intended for landscape or country-level modeling are not appropriate. Many modeling approaches were designed for even-aged applications in the wood products industry, but maple sugarbushes are often mixed-species, uneven-aged stands. Suitable carbon modeling methods are capable of analyzing mixed-species and uneven-age forest at the stand level. For temporal considerations, it is important to consider that maple sugarbush management operates along with the annual syrup production cycle, and models with the ability to increment their results in yearly time steps will be most suitable.

Though all the pools are part of forest carbon dynamics, some models eliminate certain pools in favor of reduced complexity. Including all the forest carbon pools defined by IPCC is ideal for a comprehensive model. However, there are tradeoffs between data availability and modeling resources and the ability to generate informative (though lower accuracy) results. Above-ground biomass is the primary pool impacted by maple forest management and is the top priority for modeling. Soil carbon, due to being a relatively large pool in the northern hardwood forest type, is also a priority. Necromass, the dead wood and litter pools, are important components to model because sugarbush management actions related to thinning and clearing for sap collection infrastructure directly impact this pool. Below-ground biomass is the smallest and least influenced by sugarbush management but should be included in a comprehensive model.

Other considerations for the suitability of various models in the sugarbush context are their accessibility, prior testing, and ease of use. This review of modeling options considered only those that are freely accessible, well documented, and tested on a variety of forest types, with emphasis on models useable by maple industry members, professional associations, and researchers with a range of backgrounds. An additional consideration was the models' method for estimating carbon stocks. Growth and yield models use empirical growth data as their starting point, while process-based models depend on calculating growth from equations that represent underlying photosynthetic processes (Kim et al., 2015; Mäkelä et al., 2000). One advantage of models based on empirical growth data is that they do not require detailed measurement of environmental conditions as inputs, making them more accessible (Kim et al., 2015).

Carbon models from scientific literature were reviewed by type, spatial resolution, temporal resolution, and carbon pools included. Based on these criteria, models were identified as suitable, moderately suitable, or unsuitable for application to a maple sugarbush. Suitable models are stand-level, can increment yearly, include at least the above-ground, dead wood, and litter pools, are freely accessible, and require low to moderate expertise for use. Unsuitable models are those with characteristics that make them unusable in the sugarbush context. Moderately suitable models meet the minimum requirements described but present challenges, such requiring extensive modeling experience. Descriptions of all models reviewed can be found in the SI.

Two promising models are CO2FIX and CASMOFOR, due to their characteristics and evidence of their successful use and testing. The CO2FIX model uses a growth and yield approach with the main input of stem growth, includes all the IPCC forest carbon pools, and

operates with a 1-year timestep (Schelhaas et al., 2004a). It splits forests into cohorts, groups that exhibit similar growth, to allow for modeling of multi-species and uneven-aged stands (Masera et al., 2003; Schelhaas et al., 2004b). It has been successfully implemented in recent decades for a variety of forest types, from European temperate forests to agroforestry systems in Ethiopia (Nabuurs & Schelhaas, 2002; Negash & Kanninen, 2015). The model additionally contains a tool to estimate available carbon credits, which is useful for forest managers interested in predicting this potential (Schelhaas et al., 2004a). CASMOFOR (CArbon Sequestration MOdel for FORestations) was initially developed for use in Hungarian forests, but its design allows for use in other locations and forest types. The model operates at the stand level and reports forest carbon for all IPCC pools using a 1 year timestep (Somogyi, 2023). It is freely available, and the recent versions are well-documented and targeted at general users with various backgrounds (Somogyi, 2023).

The United States and Canadian forest services have both developed forest carbon models that are freely available, well-documented, and applicable to sugarbushes, though they have some notable drawbacks. The Forest Vegetation Simulator (FVS) from the United States Forest Service is a reputable model for simulating forest vegetation that is widely used across various forest types in the United States and could be applied to a sugarbush. However, it does not account for soil carbon (Dixon, 2025). The CBM-CFS3 model from the Canadian Forest Service could be applied to a sugarbush, but it currently does not accommodate uneven-aged stands; there is a work-around option of adding additional yield curves for the different ages present, but it is less suitable at the stand level than the other models considered (Kull et al., 2024). These two models may be appropriate in some cases, but CO2FIX and CASMOFOR appear to be the most suitable for sugarbush modeling.

A table of all potentially suitable models for the sugarbush context can be found in Table 5 in the SI. Modeling carbon dynamics in maple sugarbushes is an opportunity to evaluate potential management scenarios, but field measurements remain important for management decision making for individual sugarbushes and are especially necessary when entering the carbon market.

Carbon conscious management for the maple syrup industry

Insights from other forest management methods

The maple syrup industry has mostly evolved separately from other types of agriculture and forest product industries, though experience from these industries can provide insights for carbon management in sugarbushes. Of particular value are silviculture practices from the wood products industry and agroforestry, both of which have a larger body of research on the carbon outcomes of management decisions than the maple syrup industry does.

The wood products industries of the United States and Canada have invested significant resources in evaluating silvicultural practices to optimize factors including stem volume, wildlife habitat, and carbon sequestration. Carbon sequestration has been linked to thinning methods, desired age distribution, and structural complexity in a variety of studies of maple-dominant northern hardwood forests. Thinning from below, in which stems of small diameter are removed first until a desired relative density or basal area is reached, was found to promote greater biomass production and carbon sequestration rates than the alternative methods of thinning from the middle or thinning from above (C. Hoover & Stout, 2007). Due to the sap production benefits of large trees, some sugarbush managers act to promote a more uniform distribution of older trees. However, multi-aged sugar maple-dominant forests provide greater carbon benefits, and management strategies for uneven-aged forests, such as single tree selection and irregular shelterwood thinning, have been found to promote higher carbon sequestration rates (D'Amato et al., 2011). Practices originally designed to promote bird habitat, called Silviculture With Birds in Mind, can also have carbon benefits by creating structural complexity in addition to maintaining age distribution (Thom & Keeton, 2020). These practices are compatible with sap production goals because they encourage the retention of large trees while also supporting forest longevity by promoting growth in other age classes.

Disruption of the forest floor and soil carbon is a potential concern with some silvicultural interventions. Experiments in sugar maple-dominant northern hardwood forests in north-central Wisconsin found no difference in soil and forest floor carbon pools between uncut control stands and stands where thinning treatments were applied (Jurgensen et al., 2012). This suggests that silvicultural treatments used to promote carbon sequestration through stimulating growth of live biomass can be conducted in maple forest without significant disturbance to the forest floor and soil pools.

Agroforestry, as a term and practice, is most commonly applied to tropical and subtropical agriculture, though it has gained attention in temperate environments as well. An accepted definition in the United States context is "an intensive land management system that optimizes the benefits from the biological interactions created when trees and/or shrubs are deliberately combined with crops and/or livestock" (Association for Temperate Agroforestry, 2024). Maple syrup production has a debatable claim to inclusion, since it lacks integrated cultivation with other crops or livestock. Since it involves annual harvest from trees in mixed species forests, some people consider it agroforestry, and there is potential for agroforestry practices to be used as a strategy for carbon sequestration.

In North America, agroforestry practices are divided into the categories of alley cropping, silvopasture, riparian buffers, windbreaks, and forest farming (Jose et al., 2018). Most of

these techniques involve interspersed forest and crop areas. However, forest farming, the cultivation of crops beneath a managed forest canopy, includes agricultural practices in fully forested areas and is applicable to the maple syrup industry (Kenneth Mudge, 2019). In regions with northern hardwood forests, there are a variety of crops recommended for use in forest farming. American ginseng is a high-value understory crop that is recommended in the northeast U.S. and Canada, and has been successfully cultivated in maple forests in Quebec (Kenneth Mudge, 2019; Nadeau et al., 1998). Midstory fruit trees (such as Paw paw and American persimmon), nuts (including hickory, chestnut, and hazelnut), and shiitake mushrooms are other options for forest farming (Kenneth Mudge, 2019). One example of these methods in practice is Tonoloway Farm, in the Appalachian region of Virginia, where maple, black walnut, and hickory syrups are produced alongside chestnuts, hazelnuts, and shiitake mushrooms (*Tonoloway Farm*, n.d.). Agroforestry encourages species diversity and structural layers, which leads to increased carbon sequestration by higher vegetation density and growth rates, as well as providing additional economic benefits from forest-farmed crops.

Management recommendations

Comparing sequestration and production emissions

Many producers have expressed interest in comparing their sugarbush's sequestration to the emissions from their syrup production operation. Current data are insufficient to conduct this comparison on an industry-wide scale, but some insights can be gained from existing information. Biogenic emissions are the most appropriate for comparison to forest carbon sequestration because, unlike fossil fuel emissions, they originate from carbon already in the active carbon cycle. Recent research on carbon footprinting of syrup production determined emissions ranges for different producer size archetypes (Checkoway et al., 2024). The ranges for small and medium archetypes using wood fuel, are shown in column 3 of Table 1. An average sugarbush produces about 40 gallons of syrup per acre (≈61 liters per hectare) (Brown, 2013). Assuming production volume scales linearly with sugarbush area, the emissions ranges per gallon determined by Checkoway et al. can be converted to per hectare values (in column 4 of Table 1) for comparison to carbon sequestration.

Table 1: Emissions from wood-fueled syrup production

Producer Size	**# of taps**	**Emissions range (kg CO_2e/L)**	**Emissions range (tonnes CO_2e/hectare)**
Small	< 1000	7.1 - 31.2	2.67 – 11.66
Medium	1,000 – 10,000	3.7 - 27.8	1.38 – 10.36

The USDA has published estimates of carbon stocks on reforested land by forest type and cohort age across the United States (J. Smith et al., 2006). These data account for carbon pools including live trees, standing dead trees, understory vegetation, down dead wood, forest floor, and soil carbon. The stocks for maple-beech-birch forest in the Northeast and Northern Great Lake states were used to calculate annual stock changes in accordance with the guidance provided by Smith et al., referencing the non-soil carbon stocks (the soil carbon stocks for this forest type were found to be constant). For comparison with production emissions, the annual stock changes were multiplied by 44/12, the ratio of the molecular weights of carbon dioxide and carbon, to determine the CO_2 sequestration shown in the last column of Table 2.

Table 2: Carbon stocks and stock changes for the maple-beech-birch forest in the Northeast and Northern Great Lake states of the United States

Age (yr)	**Non-soil Carbon Stock** (t C/ha) (J. Smith et al., 2006)	**Stock Change** (t C/ha/yr)	**CO_2 Sequestration** (t CO_2/ha/yr)
US Northeast maple-beech-birch forest			
5	52.2		
15	64.7	1.25	4.58
25	85.7	2.10	7.70
35	107.8	2.21	8.10
45	126	1.82	6.67
55	142.7	1.67	6.12
65	157.7	1.50	5.50
75	171.2	1.35	4.95
85	183.2	1.20	4.40
95	193.9	1.07	3.92
105	203.4	0.95	3.48
115	211.7	0.83	3.04
125	218.8	0.71	2.60
US Northern Great Lake states maple-beech-birch forest			
5	41.2		
15	39.4	-0.18	-0.66
25	57.3	1.79	6.56
35	78.2	2.09	7.66
45	96.9	1.87	6.68
55	114.8	1.79	6.56
65	131.8	1.7	6.23
75	148	1.62	5.94
85	163.3	1.53	5.61
95	177.8	1.45	5.32
105	191.6	1.38	5.06
115	204.6	1.3	4.77
125	216.9	1.23	4.51

The minimum tappable age for maples is around 30-40 years, so the sequestration values from 35 to 125 years old are most representative of a maple sugarbush. Within this age range the annual sequestration for the Northeast ranges from 2.60 to 8.10 tonnes CO_2/hectare/year and the annual sequestration for the Northern Great Lake states ranges from 4.51 to 7.66 tonnes CO_2/hectare/year. To obtain a rough comparison producers can estimate their biogenic production emissions using the carbon footprint calculator or determine where their operation falls within the emissions ranges published by Checkoway et al. and compare this to sequestration estimates for their forest type and region. The ranges shown in Table 1 as well as sample scenarios from specific producers have shown that annual carbon sequestration can fall within the range of biogenic production emissions. Understanding the realistic ranges of both production emissions and forest carbon sequestration can help inform management decisions and emissions reduction goals, but site-specific data collection is necessary as a

basis for any claims made about a particular production operation. Additionally, conducting these comparisons presents some potential pitfalls, particularly equating emissions and sequestration without properly considering additionality or the timing of production emissions and sequestration processes.

Pitfalls to avoid

Maple syrup operations encompass both GHG emissions from syrup processing as well as carbon sequestration in the sugarbush, and it is tempting to directly equate these values to determine net emissions. Measuring carbon sequestration and setting emissions reduction goals are admirable management activities, but it is critical to consider that carbon accounting guidelines have evolved to prevent counting as a credit sequestration that would have occurred without an intervention. The GHG Protocol's Corporate Accounting and Reporting Standard states the importance of including both emissions and removals from sequestration in the inventories of land-based sectors, but notes that as of the publication of the guidance, consensus on how this is done had not been reached (Janet Ranganathan et al., 2015). The more recent draft guidance for the land sector requires recording of biogenic and technological removals and assurance that all removals are monitored for ongoing storage (i.e., permanence), traceable, based on primary data, include consideration of uncertainty, and account for reversals (GHG Protocol Land Sector and Removals Guidance, 2022). The latest best practices in the compliance and voluntary carbon markets require additionality and permanence to be thoroughly demonstrated. Syrup producers should be cautious of making claims about net emissions without considering the implications their unique scenario may have on the additionality and permanence of the carbon sequestered by their sugarbush.

Double-counting credit for carbon sequestered by a sugarbush is another area of concern. For those engaging with carbon markets, the double issuance of credits is prohibited for obvious reasons, but questions of double-counting can be less clear when considering carbon benefits beyond credits, and it is important to avoid overlapping claims. For example, if sugarbush carbon sequestration credits are sold, that sequestration is no longer available to support marketing statements.

The reliance on indirect measurements and generalized equations results in uncertainty being a major concern in forest carbon measurement. Those conducting measurements and making claims about sequestration benefits should ensure they are using well-researched methods suitable for their specific forest type and location, be transparent about their process and verify the statistical significance of their results.

Concluding recommendations

This paper draws insights from sources not commonly considered by the maple syrup industry to inform carbon management practices in maple sugarbushes. Maple producers' interest in carbon management falls into the categories of stewarding their forest resources, receiving recognition for their environmental contributions, and understanding opportunities for compensation. Each of these goals has a pathway, shown in Figure 2, for carbon management actions that can lead to outcomes of reduced net emissions, potential for sales growth through green marketing, and opportunity for additional revenue through participation in carbon markets.

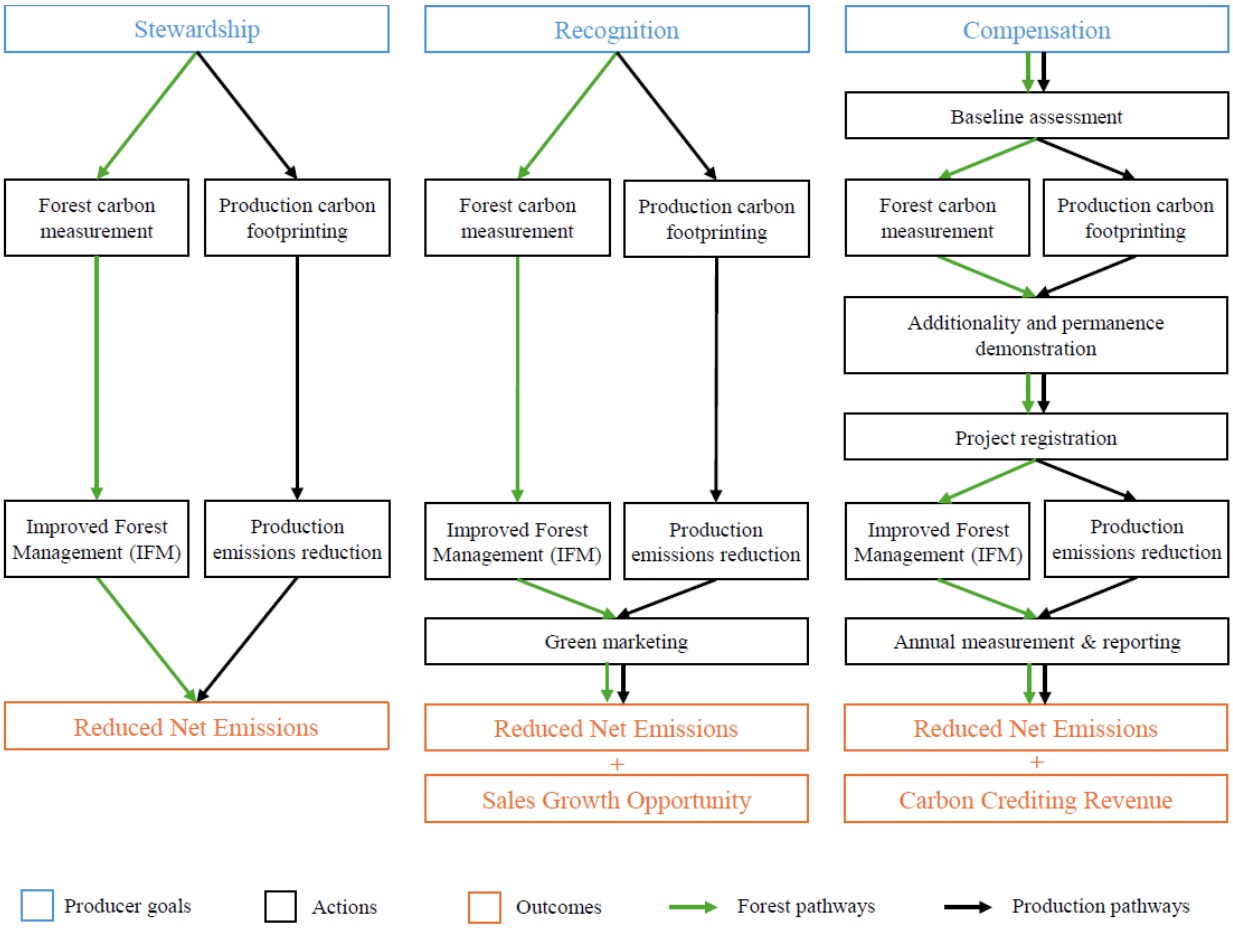


Figure 2: Pathways to potential outcomes based on producer goals

While there are anecdotal cases of syrup producers being offered payments for the carbon their forests sequester, participation in compliance or voluntary markets is limited, particularly for small operations, by the high barriers to entry and the rigorous requirements for demonstrating additionality and permanence. Moreover, even IFM projects adhering to robust standards face critiques regarding over-crediting. As a result, maple producers whose chief motivation is making a positive environmental contribution are likely to find greater success by focusing on management practices that enhance carbon sequestration and/or reduce production emissions and communicating their efforts through transparent, data-supported marketing.

The maple syrup industry has the potential to further develop management practices that support carbon sequestration goals, and efforts from research institutions interested in evaluating new methods and insights from fields like silviculture and agroforestry can help inform producers. These approaches will enable the industry's forest management practices to align with climate goals and for syrup producers to be recognized for their role in stewarding forest resources that contribute to forest Natural Climate Solutions. The presented guidance can help position the maple syrup industry as an environmental leader and can be applied by producers of other tree crops (e.g., fruits and nuts) seeking to better understand the carbon dynamics of their operations.

Future research priorities

Developing baselines, testing silvicultural treatments, and considering companion species are key areas in which future research could support the maple syrup industry's contribution to climate change mitigation. The current lack of measured carbon sequestration baselines for maple sugarbushes is an important gap to fill, and published examples would be valuable for those tracking carbon sequestration for environmental claims or considering participation in carbon markets. The silvicultural treatments found to have carbon benefits in maple-dominant forests require testing in maple sugarbushes with consideration for their alignment with other maple operations, such as tubing replacement. Additionally, modeling would help extend the insights on silvicultural treatments gained from field studies. Maple sugarbush species composition is known to be quite varied, and this is something that could be more consciously managed. Insights from agroforestry suggest evaluating understory and companion species for promoting carbon sequestration and potential added economic benefit.

The guidance for improving sequestration measurement, management, reporting and policy highlighted here provide maple sugarbush managers, syrup producers, and other key stakeholders a foundation for achieving both climate mitigation and syrup production goals, a foundation that is also applicable to other tree crop operations.

Supplementary Information

SI Table 1: Compliance and voluntary carbon market (VCM) standards reviewed

Standard	Organization	Organization Type	Standard Type	References
California Air Resources Board U.S. Forest Projects Compliance Protocol	California Air Resources Board	Government	Compliance	(Compliance Offset Protocol U.S. Forest Projects, 2015)
Climate Action Reserve U.S. Forest Protocol	Climate Action Reserve	Non-profit	VCM	(Kessler et al., 2023)
Regional Greenhouse Gas Initiative Offsets	RGGI Inc. and participating states	Government consortium	Compliance	(Regional Greenhouse Gas Initiative, 2018)
British Columbia Greenhouse Gas Offset protocol: Forest Carbon	Government of British Columbia	Government	Compliance	(Adria, 2024)
Canadian Federal Offset Protocol: Improved Forest Management on Private Land	Environment and Climate Change Canada (ECCC)	Government	Compliance	(Improved Forest Management on Private Land, 2024)
American Carbon Registry Standard	American Carbon Registry	Non-profit	VCM	(Aggregation and Programmatic Development Approach Guidance for Improved Forest Management, 2021)
Verified Carbon Standard	Verra	Non-profit	VCM	(VCS Standard, 2024)

SI Table 2: Comparison of additionality criteria in compliance and voluntary carbon market standards

	Additionality Criteria Included					References
Standard	**Legal additionality**	**Financial additionality**	**Implementation barriers**	**Performance standard**	**Common practice**	
California Air Resources Board U.S. Forest Projects Compliance Protocol	Yes Required	No	No	Yes Required	No	(Compliance Offset Protocol U.S. Forest Projects, 2015)
Climate Action Reserve U.S. Forest Protocol	Yes Required	No	No	Yes Required	No	(Kessler et al., 2023)
Regional Greenhouse Gas Initiative Forest Offset Protocol	Yes Required	No	No	Yes IFM projects automatically pass	No	(US Forest Projects Offset Protocol, 2013)
British Columbia Greenhouse Gas Offset protocol: Forest Carbon	Yes Required	Yes Required	No	No	No	(Adria, 2024)
Canadian Federal Offset Protocol: Improved Forest Management on Private Land	Yes Required	No	No	Yes IFM projects automatically pass	No	(Improved Forest Management on Private Land, 2024)
The American Carbon Registry Standard	Yes Required	Yes Only required if there are no technological or institutional barriers	Yes Choice of 3 barriers to satisfy: financial, technological, institutional	Yes As an optional alternate path	Yes Required	(The ACR Standard, 2023)
Verified Carbon Standard	Yes Required	Yes Required	Yes Required	No	Yes Required	(VCS Standard, 2024) (VCS Additionality Assessment, 2024)

SI Table 3: Comparison of permanence criteria in compliance and voluntary carbon market standards

	Permanence Criteria				References
Standard	**Permanence monitoring**	**Buffer pool required**	**Risk assessment required**	**Reversal compensation required**	
California Air Resources Board U.S. Forest Projects Compliance Protocol	**100 yrs**	**Yes** 15-20% of credits	**Yes**	**Yes**	(Compliance Offset Protocol U.S. Forest Projects, 2015)
Climate Action Reserve U.S. Forest Protocol	**100 yrs**	**Yes** 15-20% of credits	**Yes**	**Yes**	(Kessler et al., 2023)
Regional Greenhouse Gas Initiative Forest Offset Protocol	**100 yrs**	**No**	**Yes**	**Yes**	(US Forest Projects Offset Protocol, 2013)
British Columbia Greenhouse Gas Offset protocol: Forest Carbon	**100 yrs**	**Yes** 18-40% of credits	**Yes**	**Yes**	(Adria, 2024)
Canadian Federal Offset Protocol: Improved Forest Management on Private Land	**100 yrs**	**Yes**	**Yes**	**Yes**	(Improved Forest Management on Private Land, 2024)
The American Carbon Registry Standard	**40 yrs**	**Yes** 10-20% of credits	**Yes**	**Yes**	(The ACR Standard, 2023)
Verified Carbon Standard	**40 yrs**	**Yes** 10-40% of credits	**Yes**	**Yes**	(VCS Standard, 2024)

SI Table 4: Sources of guidance informing current best practices in forest carbon management

Name	Purpose	Organization	Organization Type	References
Forest, Land, and Agriculture, Science-Based Target-Setting Guide	Guide companies in land-intensive sectors to design GHG emissions and removal targets aligned with the Paris Agreement	Science Based Targets Initiative	International NGO	(Anderson et al., 2023)
Greenhouse Gas Protocol Land Sector and Removals Guidance	Provide best practices for GHG accounting, reporting, and management in the land sector	World Resources Institute	International NGO	(GHG Protocol Land Sector and Removals Guidance, 2022)
Core Carbon Principles	Define high quality credits in the Voluntary Carbon Market	Integrity Council for the Voluntary Carbon Market	Non-profit	(Core Carbon Principles Assessment Framework and Procedure, 2024)
ISO 14064-2	Set a standard for quantifying, monitoring, and reporting GHG emissions reductions at the project level.	International Organization for Standardization	International standard body	(*ISO 14064-2*, 2019)
ISO 14067	Set a standard for quantifying and reporting the lifecycle carbon footprints of products.	International Organization for Standardization	International standard body	(*ISO 14067*, 2018)

SI Table 5: Forest carbon models reviewed for applicability to the sugarbush context

Name	Creator	Type	Spatial Resolution	Temporal Resolution	Carbon Pools	References
CO2FIX	Wageningen University	Growth and yield	Stand	1 year	☑ Above ground ☑ Below ground ☑ Dead wood ☑ Litter ☑ Soil ☑ Wood products	(Schelhaas et al., 2004a) (Schelhaas et al., 2004b) (Masera et al., 2003)
CASMOFOR	Zoltán Somogyi	Growth and yield	Stand	1 year	☑ Above ground ☑ Below ground ☑ Dead wood ☑ Litter ☑ Soil ☒ Wood products	(Somogyi, 2023a) (Somogyi, 2023b)
Forest Vegetation Simulator (FVS)	US Forest Service	Growth and yield	Stand – landscape	1 year minimum	☑ Above ground ☑ Below ground ☑ Dead wood ☑ Litter ☒ Soil ☑ Wood products	(Dixon, 2025)
CBM-CFS3	Canadian Forest Service	Growth and yield	Stand – landscape	1 year	☑ Above ground ☑ Below ground ☑ Dead wood ☑ Litter ☑ Soil ☑ Wood products	(Kull et al., 2024)
3-PG	Forest Research New Zealand	Process-based	Stand – landscape	1 month	☑ Above ground ☑ Below ground ☒ Dead wood ☒ Litter ☑ Soil ☒ Wood products	(Landsberg & Waring, 1997) (Forrester, 2021)

SI Table 6: Models found to be unsuitable for use in the maple sugarbush context

Model	**Reasons for lack of suitability**	**References**
BIOME-BGC	• Timestep of 1 day • Aimed at users with expert modeling capabilities	(Thornton, 2000)
LANDIS-II	• For large spatial resolutions of hundreds to millions of acres • Aimed at users with expert modeling capabilities	(LANDIS-II Foundation, n.d.)
EFISCEN	• For large spatial resolutions, from landscape to region level	(Kim et al., 2015)
GAYA 2.0	• The code for the 2.0 version is not publicly available at this time • Best for longer timesteps and harvesting scenarios	(Strîmbu et al., 2023)

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