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ORIGINAL PAPER

Voluntary Sustainability Standards and Operation Size and Age Influence Forest Characteristics in Vermont Sugarbushes

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Abstract

The social, ecological, and economic value of non-timber forest products is considerable, but their management in North America is understudied, as is the effect of their harvest on the ecosystems that produce them. Maple sap and syrup are non-timber forest products of longstanding importance throughout North America, including in Vermont, which supplies more than half of all United States output. Production of maple in Vermont has swiftly risen since ~ 2010, yet stewardship practices used to supply this product and resultant forest conditions are poorly understood, including impacts from changes in sap collection systems over the past several decades. We analyzed 99 forest management plans for sap producing forests ("sugarbushes") enrolled in the "current use" tax abatement program in Vermont, investigating the role of voluntary sustainability standards, specifically USDA organic certification and Bird-Friendly Maple recognition, along with the effect of sugaring operation size and age on forest structure, composition, and management activities. Engagement with sustainability standards was associated with greater overstory species diversity, with large operations (> 10,000 taps) organic certified at higher rates than small (> 1,000–4,999 taps). More recently (≥ 2010) tapped sugarbushes were also associated with greater overstory diversity, while older operations (< 2010) were characterized by larger trees and higher live-tree stocking. Our findings highlight the potential benefit of voluntary sustainability standards to biodiversity. In addition, the limited range of forestry activities reported stresses the need for updated silvicultural guidance to sustain forest ecological conditions and account for the unique operational considerations in sugarbushes relative to management for traditional wood products.

Keywords Non-timber forest products · Maple · Certification · Sugar maple · *Acer saccharum* · Sugarbush

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Introduction

Non-timber forest products (NTFP) have been used and valued for thousands of years, predating the modern dominance of wood production as the core utility of forests (FAO 1995). NTFPs include a wide range of foods, medicines, materials, products, and services that are derived from forests, excluding timber, and they are especially important for rural and subsistence livelihoods (Hinrichs 1998; Leßmeister et al. 2018; Derebe et al. 2023). NTFP are also harvested recreationally (McLellan and Brown 2017) and can include different plant parts, such as roots, fruits, foliage, and sap. Despite their role in providing direct resources, as well as employment and income, the economic value and sustainable management of NTFPs have often been overlooked (FAO 1995; Murphy et al. 2012; Chamberlain et al. 2019).

The limited oversight associated with NTFPs stems in part from the difficulty in tracking their harvest and sale, as some NTFPs never leave rural communities or enter the commercial market (Leßmeister et al. 2018; Chamberlain et al. 2019; Frey et al. 2023). Additionally, many species and products can be classified as NTFPs, which can lead to insufficient knowledge of their harvest levels, rates of recovery, and best management practices (Ticktin and Shackleton 2011; Chamberlain et al. 2019). Despite the significant social and economic value of NTFPs, the integration of their management with timber to further develop sustainable forest management practices has been limited and managers often lack the skills and tools to adequately address their sustainable management (Miina et al. 2020; Sheppard et al. 2020).

The governance of many NTFPs is complicated. Some may be under the purview of legislation and regulation by the government, meanwhile others are governed solely by social norms and voluntary policies or a combination of the two (Murphy et al. 2012; Wiersum et al. 2014). Concerns over biodiversity loss and unsustainable harvesting led to the creation of global forest certification in the 1990s (Rametsteiner and Simula 2003). Certification represented a market-based solution to promote sustainable forest management, verify its implementation, and receive price premiums (Rametsteiner and Simula 2003). Over time, these timber-focused certification programs expanded to include NTFPs. Routes for certification have grown and now cover growth and harvest (e.g., organic certification, wild collection standards), labor practices (e.g., fair labor standards), and production (e.g., lifecycle certification, corporate accountability standards) (Pierce et al. 2008; Chittum et al. 2019; Frey et al. 2023). These varying forms of governance, along with ecological and socio-economic factors, significantly impact the sustainability of NTFP harvesting (Ticktin and Shackleton 2011). Certification schemes have been successful in raising purchase prices, increasing harvester income, altering forest management planning and practices, and protecting forest quality for some NTFPs (Duchelle et al. 2014; Girma and Gardebroek 2015; Takahashi and Todo 2017).

Maple sap is an important NTFP produced solely in coterminous North America. Maple sap and syrup are part of the rich cultural heritage of many Tribal

Nations, including those of the Wabanaki, Haudenosaunee, and Anishinaabe, where maple is an essential part of traditional lifeways and element in stories and legends (Keller 1989; Kuhnlein and Turner 1991; Harper and Ranco 2009). This long-standing relationship continues into the present day and serves as a valuable model for addressing present-day challenges to sugarbush stewardship (Ahmed et al. 2023). Maple is now a multi-million-dollar industry, as the value of 2022 production across Canada and the United States (US) was estimated at $696.3 million (USD), with approximately 31% of that attributed to the US (Agriculture and Agri-Food Canada 2023; USDA Nass 2024a). Lack of information on the ecological conditions of and management approaches in forests used for collecting sap to produce maple syrup (hereafter referred to as "sugarbushes") presents a serious limitation to understanding and addressing immediate and future challenges to sugarbush health and productivity, as well as wider sustainability issues, such as biodiversity and carbon sequestration and storage, present for this regionally important resource.

Maple sap and syrup are NTFPs that often fall under the jurisdiction of both forest and agricultural management standards. As a result, sugarbush management guidance and regulations may often include practices tied to organic food production, as well as those focused on sustainable forest management. For example, sap production in many states may engage with organic certification, which usually includes stipulations around levels of tree diversity in sugarbush stands, management for multiple age classes, and prohibitions on herbicide and pesticide use (e.g., PCO 2020; MOFGA 2022; VOF 2024). Meanwhile, these same forests may be enrolled in state property tax abatement programs, commonly referred to as "current use" programs. These voluntary government programs usually require the preparation of formal forest management plans, which demonstrate adherence to silvicultural methods appropriate for the forested ecosystems from which sap is collected, typically sugar maple (*Acer saccharum*)-dominated forests, and application of best management practices to protect soil, water, and biodiversity (Kilgore et al. 2018). Given the emphasis of timber management practices by most current use programs, it is unclear how forests stewarded for maple sap may differ in management strategies applied and forest conditions created.

Over the past several decades maple sap collection and syrup production has undergone a host of changes. For large operations, the iconic cultural image of bucket collection systems has given way in large part to plastic tubing collection systems, using vacuum pumps to increase efficiency and sap flow, both of which emerged in the latter part of the twentieth century (Smallidge et al. 2022; Thomas and Koelling 2022). Use of reverse osmosis and nanofiltration to pre-concentrate sap before boiling is now a common practice and oil-fired evaporator use has also risen, although many sugar makers still heat with wood and procure fuel from their forests. Despite the many significant changes that have taken place in the industry, management guidance for sugarbushes has been slow to catch up. Early guides were developed for grazed or post-agricultural woodlots that used buckets, favoring fewer trees per acre with deep crowns and, ideally, high sugar content in their sap, conditions less reflective of modern-day sugaring operations (Smallidge et al. 2022). Sugarbush-specific silvicultural management research has been limited, and management guidelines often reference those developed for timber (Lancaster et al. 1974; Smallidge et al. 2022). For example, a survey of foresters practicing in the northeastern US found only 27% of respondents referenced the *North American Maple Syrup Producers Manual* when developing management plans for sugarbushes and less than 10% used developed silvicultural guidance, such as Houston et al. (1990) and Lancaster et al. (1974) (Isselhardt et al. 2022). It is unclear whether the silvicultural practices designed to produce timber are best suited to maintain or enhance a productive sugarbush. As the sugaring industry grows to occupy a greater proportion of northeastern forest lands, it is important to characterize contemporary sugarbush management approaches, understand their impact, and develop best practices.

Vermont (VT) is the leading US producer of maple syrup, supplying about 3.2 million gallons in 2022, which is approximately 54% of US total production and valued at $112.1 million (USD) (USDA Nass 2024b). Expansion of sugaring in VT began in the 2000s, with rapid growth through the 2010s and early 2020s. An estimated 18 million taps were set in VT in 2022, more than four times the estimate 10 years prior, with the number of operations with 10,000 + taps more than doubling (USDA Nass 2014; 2024b). A tap is a spout driven into a tree and used to collect sap. The recommended amount of taps used per tree depends on the size of the spout and the diameter at breast height (DBH) of the tree (Perkins et al. 2022). Trees of adequate size can have one or more taps, meaning that tap count is not directly comparable to forest basal area or trees per hectare. This adds complexity when translating traditional timber approaches to sugarbush management.

Within VT, sugarbushes are eligible for enrollment in several programs focused on improving their management and condition. Sugarbushes may enroll in the state's Use Value Appraisal (UVA) tax abatement program, which is a voluntary governmental program, assessing enrolled lands at their agricultural or forest value, instead of their fair market (i.e., development) value, to reduce financial pressures on landowners and keep forest and farmland undeveloped. Additionally, sugarbushes may be organic certified and/or recognized by the Bird-Friendly Maple (BFM) program, adhering to voluntary sustainability standards (VSS) (VOF 2024; Audubon Vermont n.d.). VSS are non-compulsory, non-governmental approaches to promoting sustainability through defined and transparent standards and practices that are audited (Komives and Jackson 2014). Specifically, BFM recognition refers to a program administered by the Audubon Society and focused on maintaining and/or creating high-quality habitat for priority bird species within sugarbushes, whereas organic certification of maple is administered by multiple organizations, each with their own developed guidance, generally prohibiting the use of synthetic materials in management and production and promoting practices to maintain tree and ecosystem health.

The present study reviewed forest management plans (FMPs) from 99 parcels enrolled in the UVA program in VT, all of which reported sugarbush management and a parcel-level tap count of > 999 taps. A subset of these parcels were organic certified and/or BFM recognized. This study assesses the impact of these governance approaches on management actions and outcomes for sugarbushes. Specifically, we investigate the effect of UVA enrollment, organic certification, and BFM recognition on tree species diversity, recruitment of biological legacies, and the presence of introduced species. We also investigate the influence of sugaring operation size and age on sugarbush structure, composition, tapping density, and management activities. These elements of sugarbush management can directly impact the sustainability of NTFP harvesting and associated biodiversity (Chapeskie et al. 2006; Smallidge et al. 2022).

Study Area and Methods

Study Area

Our work focused on VT, which is the leading US producer of maple syrup with an estimated 57,000 ha in maple production (USDA Nass 2024c). This accounts for 44% of US total sugarbush area, more than double that of land tapped in New York, which has the second most area in sugarbush (USDA Nass 2024c). Production in VT is concentrated in Franklin, Lamoille, and Orleans counties, which each accounted for 29%, 15%, and 10% respectively of syrup produced in the state in 2022 (USDA Nass 2024b). Based on 2011 U.S. Department of Agriculture, Forest Service (Forest Service) Forest Inventory and Analysis (FIA) data, Farrell (2012) estimated 6.3 million potential sugar maple taps were available in privately owned VT forests with 147 + available taps per hectare within 0.8 km distance to an access road and 56.5 million sugar and red maple taps were available in stands with 74 + taps per hectare within 1.6 km from an access road. Without accounting for ingrowth, mortality, or changes in land use, tapping in VT based on National Agricultural Statistics Service (NASS) 2022 census data accounts for 134% of the former estimate and 15% of the latter. According to 2024 FIA estimates, VT has approximately 1.8 million forested hectares, with forest types consisting of a significant maple component (maple-beech-birch group) constituting 71% of that total. Narrowing the focus to privately owned large-diameter stands, the current tapped estimate accounts for 7.8% of this maple-dominated resource, even while production has been on the rise (Forest Service 2025).

This study was conducted through a review of FMPs for parcels actively enrolled in the UVA program in VT. Sugarbushes may enroll in either the forest or agricultural category of the program. For those enrolled in the forest category, a FMP and adherence to sugaring standards are required (VT Fpr 2010, 2015), providing government oversight on the harvesting of maple sap and management of sugarbushes. To qualify for enrollment in the forest category of UVA, parcels must have a minimum of 10.1 ha with 8.1 ha of those in productive forest land (VT Fpr 2010). Enrollment places a lien upon the land, allowing the state to collect a land use change tax should the parcel be developed.

Parcels enrolled in the UVA program can also engage with VSS through certification and recognition programs. In 2022, NASS estimated 1,433 total operations produced maple sap in VT (USDA Nass 2024b), which may be an undercount. As of April 2025, approximately 340 producers were listed as accredited for the production of organic maple sap on the USDA Organic Integrity database (USDA 2025), representing just under 25% of estimated total operations. Organic certification was provided by four different organizations with Vermont Organic Farmers (VOF) responsible for the vast majority. Organizations that accredit organic maple production create guidelines that must comply with the USDA National Organic Program Standards. There are no maple specific national guidelines currently and the standards set by each accrediting organization vary. Additionally, sugarbushes in VT can be recognized by the Audubon BFM program. As of January 2025, approximately 90 producers in VT were enrolled in the BFM program (Hagenbuch, personal communication, January 22, 2025). The standards of the UVA, VOF, and BFM programs relevant to the data we collected are compared in Online Resource 1.

Sample Selection

Publicly available data provided by the Vermont Department of Forests, Parks, and Recreation was used to generate a sample pool of parcels with active sugarbushes enrolled in the forest category within the UVA program. Sugarbushes enrolled in the agricultural category of UVA were excluded due to their lack of a publicly available FMP. To qualify, parcels needed to report sugarbush management via the Management Activities section of the UVA Parcel Data Entry Form, a document required in the FMP, as well as the number of taps producing sap on the parcel via the UVA Forest Management Activity Report (VT Form FMR-318), a document required by the Vermont Department of Taxes for enrolled parcels. The sample was refined through the exclusion of all parcels reporting < 1,000 taps on their most recent FMR to exclude hobby producers and focus on commercial maple enterprises, yielding 176 parcels. The pool was then divided into three groups by parcel-level production size: Small, Medium, and Large. Parcels reporting 1,000–4,999 taps were classed as Small, those reporting 5,000–9,999 taps were classed as Medium, and those reporting 10,000 + taps were classed as Large. These bins follow those of previous research on maple in the northeast US (e.g., Cannella et al. 2021) in order to emphasize part- or full-time management models over hobby or lifestyle enterprises that are common at very small scales. In 2022, producers with 10,000 + taps accounted for 71.9% of total VT maple syrup production, while those with 4,999–9,999 taps accounted for 15.8% and those with 1,000–4,999 taps accounted for 10.8% (USDA Nass 2024b). Influenced by this distribution, our study sampled 99 FMPs. All FMPs in the Large class were selected (41), 31 were randomly sampled from Medium, and 27 from Small.

Statistical Analysis

All statistical analysis was conducted in R (R Core Team 2024) using RStudio (Posit team 2024). Analysis of Variance (ANOVA) (*stats* package; *aov* function) was used to compare the proportion of the total parcel used for sugaring (%), average density of taps per sugarbush hectare, and sugarbush basal area (m^2/ha) by production class (R Core Team 2024). Estimated marginal means (*emmeans* package; *emmeans* function) were used to determine significant ($\alpha = 0.05$) differences in a post hoc comparison between production classes (Lenth 2024). Kruskal–Wallis test (*stats* package; *kruskal.test* function) was used to compare quadratic mean stand diameter (QMSD) by production class. Pearsons' chi-square tests (*stats* package; *chisq.test* function) were used to compare overall participation in organic and BFM programs by production class. A pairwise test of independence for nominal data (*rcompanion* package; *pairwiseNominalIndependence* function) was used for post hoc comparison (Mangiafico 2024). See Online Resource 2 for more detail on how sugarbush composition and structure data were summarized from FMPs, along with methods used for estimation of carbon storage.

Nonmetric multi-dimensional scaling (NMDS) was used to examine parcel and sugarbush attributes across production classes and VSS (*vegan* package; *metaMDS* function) (Oksanen et al. 2024). NMDS is an ordination technique that uses repeated measures of ranked distances to display values on a predetermined number of axes with the focus of a decrease in 'stress' (McCune and Grace 2002). Bray–Curtis distances were used to calculate the distance matrix. Ordination started with a 6-axes solution and utilized a successive stepwise decrease in axes with a final stress value of < 0.2 as acceptable. Vector fitting (*vegan* package; *envfit* function) was utilized to explore the connection between axes of the NMDS and four parcel level factors: overall tap count, average tap count per sugarbush hectare, proportion of total parcel utilized for sugarbush, and the average metric tons of carbon dioxide stored per sugarbush hectare (t/ha). The above vector fitting procedure was also used to ascertain significant relationships in the ordination space for elements of parcel configuration and sugarbush structure and composition. Using indicator analysis (*labdsv* package; *indval* function), variables within the ordination with significant fidelity to specific production classes and VSS were identified (Roberts 2023). A PER-MANOVA (*vegan* package; *adonis2* function) was used to distinguish differences in sugarbush parcels between production classes, as well as VSS (i.e., no certification, organic certification, and organic certification and BFM recognition), with subsequent pairwise comparisons (*pairwiseAdonis* package; *pairwise.adonis2* function) (Martinez Arbizu 2017). PER-MANOVA tests are non-parametric and use random permutations to compare the centroids and dispersion within and among groups. The homogeneity of group dispersions was also evaluated (*vegan* package; *betadisper* function).

The comparison of program standards (Online Resource 1) was used to identify areas of commonality and difference in program governance and informed the comparisons of parcel attributes among VSS engagement. The breadth of these comparisons were limited by the small sample size. Pearsons' chi-square tests were used to compare parcels with at least one sugarbush stand with 1) $> 75\%$ of the canopy in sugar maple, 2) a reported presence of non-native introduced plant species (NNIS), and 3) targets for snag and cavity recruitment and maintenance to parcels without. A pairwise test of independence for nominal data was used for post hoc comparison.

We were interested in examining how duration of sugaring may influence management strategies and forest conditions, so further partitioned the data into sugarbushes tapped before 2010 and those tapped in 2010 or after, to reflect the rapid expansion of sugaring that took place starting around 2010 and capture changes to the industry following the strategic reserve implementation and production quotas set by the Quebec Maple Syrup Producers association in the 2000s (Gehrke 2022).

Parcels in the study had one or more forest stands that were managed as sugarbushes. Out of the 251 sugarbush stands, 148 included information on the timing of tapping initiation at the stand level, representing 67 parcels. Five parcels contained sugarbush stands tapped both before and after 2010. A random sample was selected from these instances resulting in a total of 140 sugarbush stands for this analysis, which used a weighted parcel level average. This accounted for approximately 62.7% of all sugarbush hectares in the total sample. See Online Resource 2 for detailed discussion of the curation of sugarbush data by operation age. PER-MANOVA tests were then used to elucidate differences based on operation age, followed by indicator analysis to determine significant relationships with parcel attributes. Pearsons's chi-square test was used to compare operation age among production classes and VSS.

Within the FMP, activities for each sugarbush stand are scheduled for a 10-year period, after which the plan is again updated. Details on how management activities were summarized from FMPs is available in Online Resource 2. PER-MANOVA tests were used to explore differences in sugarbushes based on scheduled management activities and indicator analysis applied to determine significant relationships with scheduled management activities. This same procedure was then repeated with the reduced dataset of sugarbushes with operation age data. To examine how sugarbush management activities compared with forest parcels managed for other objectives, we used previously summarized data on management activities scheduled through the UVA program for all enrolled forest parcels in Windsor county in 2017 (Nevins 2019). This convenience sample provided an opportunity to contrast management activities in forest parcels with low sugaring activity (Windsor county produced less than 2.5% of all VT syrup in 2022 (USDA Nass 2024b)) with those in our sample (excluding parcels in Windsor county), using a two-sample Kolmogorov–Smirnov test (*stats* package; *ks.test* function). See Online Resource 2 for information on how data from Windsor county was curated.

Results

FMPs in our sample were written by professional foresters working for 31 different companies. One company accounted for 39% of all plans sampled, with the next most prevalent company accounting for 10%. Seventeen companies produced only one plan in the sample. Although landowners have the option to write FMPs for their own parcels within UVA, all plans in the sample were produced under the direction of a licensed VT forester. Plans were dated between 2015 and 2025 and ranged in length from 4 to 88 pages, with an average length of 27 pages.

Every county in VT, excluding Grand Isle, was represented in the dataset by at least one plan. Franklin county was the most represented, accounting for 29% of all FMPs and 41% of the Large production class. Parcels were clearly clustered in Franklin, Lamoille, and Orleans counties, which occupy the north-central portion of the state (Fig. 1). These three adjoining counties accounted for 68% of all parcels in the sample and 71% of the Large production class. Parcels in the sample accounted for 8,558 ha of sugarbush, roughly 15% of the total estimated tapped land base of VT (USDA Nass 2024c).

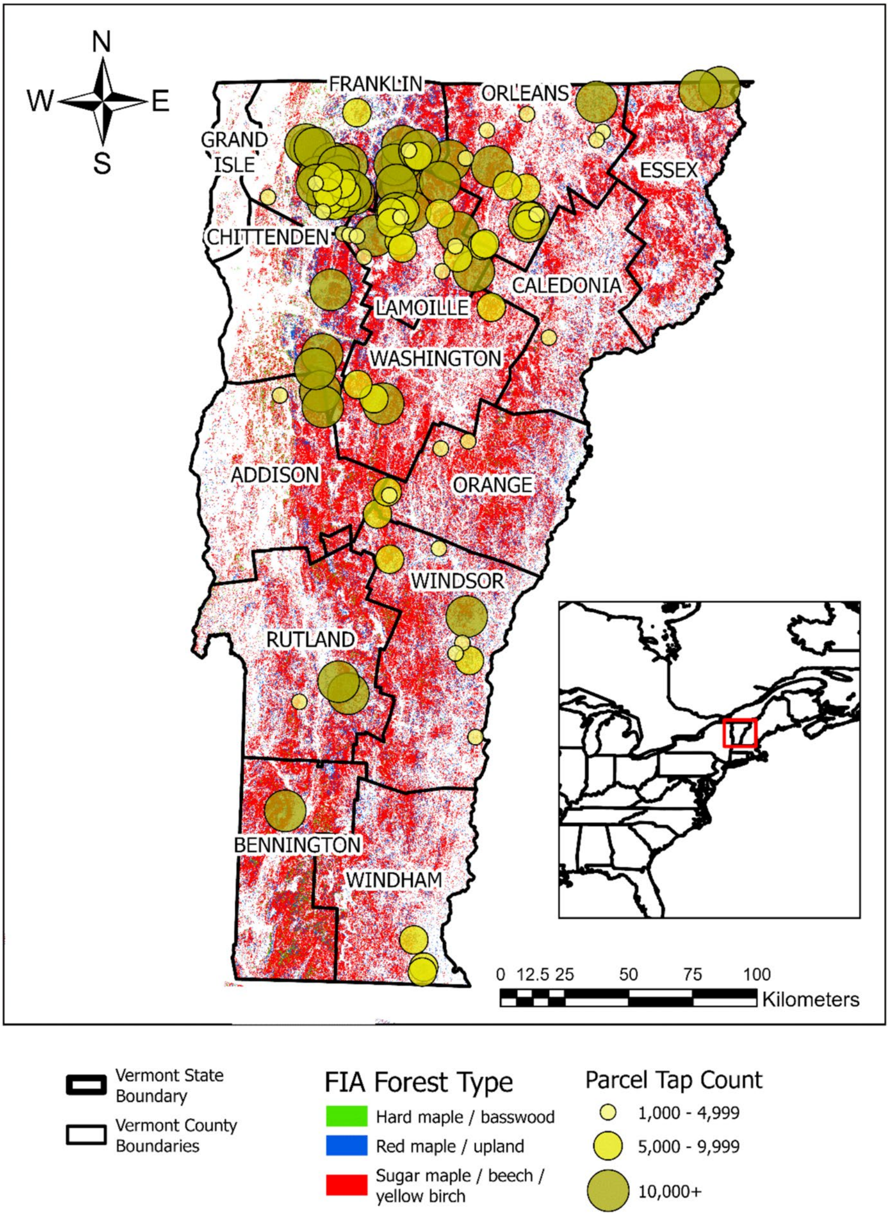

Fig. 1 Study sites across Vermont and the presence of suitable cover types for sugarbush management based on U.S. Department of Agriculture, Forest Service Forest Inventory and Analysis data (Riley et al. 2021)

Voluntary Sustainability Standards

All parcels within the sample were enrolled in the UVA program and could be additionally organic certified or BFM recognized (Table 1). All BFM recognized

Table 1 Number of plans sampled within the three parcel-level production classes and the number of individual sugarbush stands they represent for the total sample, organic certified parcels, and parcels with both Bird-Friendly Maple (BFM) recognition and organic certification. All parcels enrolled in BFM were also organic certified

	Small (1,000–4,999)	Medium (5,000–9,999)	Large (10,000+)	Total
Total number of parcels	27	31	41	99
Total number of sugarbush stands	36	64	151	251
Number of organic certified parcels	10	18	28	56
Number of organic certified sugarbush stands	12	37	91	140
Number of BFM recognized & organic certified parcels	2	6	9	17
Number of BFM recognized & organic certified sugarbush stands	2	15	25	42

parcels were also organic certified. VOF accounted for more than 91% of organic certifications, with Ecocert SAS providing the remainder. There were 36 sugarbush stands from 32 parcels where sugar maple accounted for > 75% of the total overstory composition. Although the guidelines for all programs (Table 2) require a minimum of 25% of the canopy to be in non-sugar maple, a chi-square test revealed (X^2 (2, n = 99) = 10, p = 0.006) parcels not enrolled in a VSS program to be significantly more likely to have at least one sugarbush stand not complying with this condition (i.e., > 75% sugar maple) than either organic or organic and BFM enrolled parcels (Fig. 2). The requirements related to the description and management of NNIS differ slightly between programs (Table 2), although engagement with VSS showed no noticeable effect on the reported presence of NNIS (X^2 (2, n = 93) = 3, p = 0.300) (Fig. 2). Fifty sugarbush stands across 27 parcels reported NNIS presence and six parcels did not report NNIS status in any sugarbush stand. Another noticeable difference between program requirements surrounds legacy retention (i.e., snags, cavity trees, and downed woody material) (Table 2). BFM guidelines provide the most specific requirements and set minimum targets for legacy retention that are not required by the UVA program or VOF certification. Snag targets were detailed in the FMPs of 16 parcels. However, there was no clear difference (X^2 (2, n = 99) = 0.9, p = 0.653) in the presence of snag targets when compared by engagement with VSS (Fig. 2).

Production Classes

Parcels in the Large production class were substantially more likely ($F_{2, 96}$ = 5.96, p = 0.004) to tap a greater proportion of the total parcel than those in the Small production class, although the average number of taps per hectare ($F_{2, 96}$ = 0.07, p = 0.939) showed no significant differences among production classes (Fig. 3). Large production parcels were noticeably more likely to be organic certified (X^2 (2, n = 99) = 6.51, p = 0.039) than Small, however no significant differences were observed for engagement with BFM recognition (X^2 (2, n = 99) = 2.57, p = 0.276) (Fig. 3). Small production parcels (23.7 m^2/ha ± 0.7 (SE)) had significantly higher

Table 2 A selection of the comparison of guidelines applied to sugarbushes through the Vermont Use Value Appraisal program (2010, 2015), organic accreditation through Vermont Organic Farmers, LLC (2024), and Audubon Vermont's Bird-Friendly Maple program (n.d.). UVA guidelines apply to sugarbushes enrolled in the forest, and not agricultural, category of the program, as sugarbushes may enroll in either. Organic guidelines must comply with USDA National Organic Program standards. The complete table can be found in Online Resource 1

	Vermont Use Value Appraisal Program Guidelines	Vermont Organic Farmers, LLC Guidelines for Certification of Organic Maple Sap & Syrup	Audubon Vermont Bird-Friendly Sugarbush Management Guidelines
Diversity standards	Required: + Minimum 25% of total basal area in non-sugar maple species + Where below 25% already, diversity levels not to decrease following treatment + Where below 25% already, increase of diversity a long-term management goal addressed in the FMP	Required: + *Must meet with UVA Guidelines* + FMP addresses how forest diversity will be maintained or achieved over time + Ecologically sensitive areas identified & protected in FMP, if present	Required: + FMP addresses how forest diversity will be maintained or achieved over time + Minimum 25% of total basal area in non-sugar maple species + Where below 25% already, increase of diversity a long-term management goal addressed in the FMP + Stands managed in consideration of their natural community (e.g., not unduly promoting maple on a site where it is an associate)
	Recommended: + Stands managed in consideration of their natural community (e.g., not unduly promoting maple on a site where it is an associate) + ESTA designation can be used to protect, enhance, or maintain ecologically significant features	Recommended:	Recommended:
Non-native & introduced species	Required: + Presence reported by species & categorized as light, moderate, or heavy in infestation	Required: + *Must meet with UVA Guidelines* + If control is determined necessary, methods laid out in FMP & no prohibited herbicides used	Required: + If present, a plan for their eradication & control laid out in FMP

Table 2 (continued)

	Vermont Use Value Appraisal Program Guidelines	Vermont Organic Farmers, LLC Guidelines for Certification of Organic Maple Sap & Syrup	Audubon Vermont Bird-Friendly Sugarbush Management Guidelines
Deadwood management	Required:	Required: + Whole tree harvest is prohibited + Any woody material < 3″ (7.6 cm) left in the woods	Required: + Snag & cavity trees to be retained or recruited at 2 snags/cavity trees/ac > 10″ DBH minimum (4.9/ha > 25.4 cm) + Coarse woody material to be retained or recruited at 4 logs/ac > 10″ DBH & > 3' long minimum (9.9/ha > 25.4 cm & > 0.9 m long) + Whole tree harvest is prohibited + Any woody material < 3″ (7.6 cm) left in the woods
	Recommended: + Minimize wood removed by annual clearing around lines + Leave wood from annual line clearing on-site to enhance coarse woody material	Recommended:	Recommended: + Slash left high & not lopped

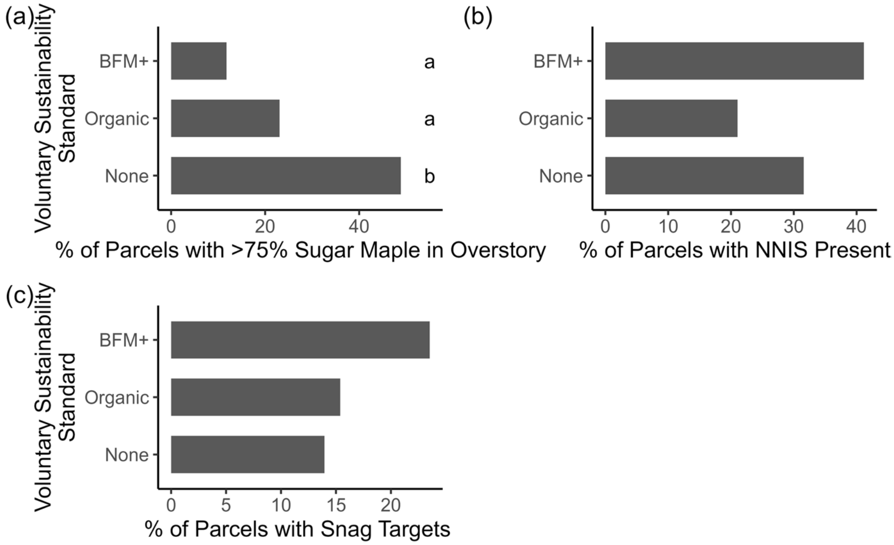

Fig. 2 The percent of parcels within each voluntary sustainability standard group with **a** greater than 75% of sugarbush overstory comprised by sugar maple, **b** non-native introduced species (NNIS) present on the parcel, and **c** an identified target for snag tree creation and maintenance. 'BFM+' represents sugarbushes both recognized by Audubon's Bird-Friendly program and organic certified. 'Organic' represents sugarbushes with organic certification alone. 'None' represents sugarbushes enrolled in Use Value Appraisal (UVA) with no additional certification or recognition. Statistically significant differences (α =.05) between groups are denoted with different lowercase letters

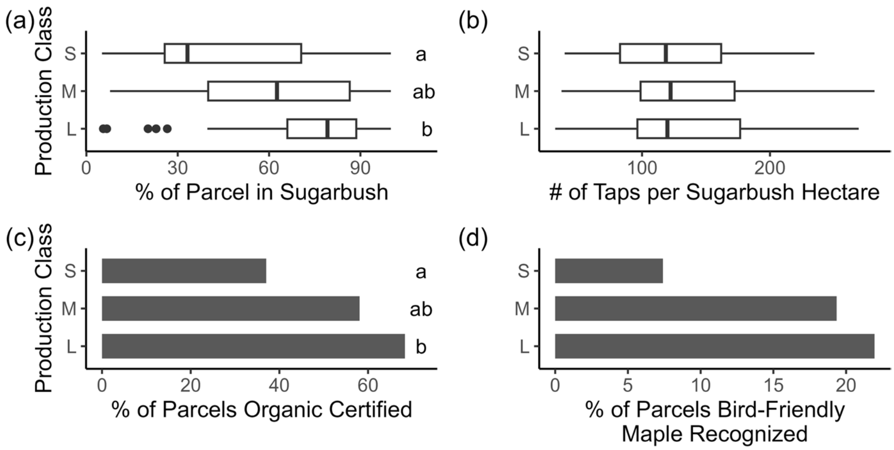

Fig. 3 The proportion of **a** the total parcel utilized as sugarbush, **b** average number of taps per sugarbush hectare, **c** proportion of the parcels with organic certification and **d** recognized by Audubon's Bird-Friendly program. Small (S) production sugarbushes had 1,000–4,999 taps, Medium (M) had 5,000–9,999 taps, and Large (L) had 10,000+taps. Statistically significant differences (α =.05) between groups are denoted with different lowercase letters

($F_{2, 96}=4.96$, $p=0.014$) total basal area than Large (21.6 m^2/ha ± 0.5) and Medium (21.3 m^2/ha ± 0.6), although there was no difference in average QMSD (H (2) = 1, $p=0.500$) between Small (28.8 cm ± 0.9 (SE)), Medium (27.7 cm ± 0.8), and Large (27.8 cm ± 0.4) sugarbushes.

There were distinct patterns in parcel size and configuration and sugarbush structure and composition across production classes, as reflected in the NMDS ordination for parcels in the sample, which was best explained by a two-axes solution (final stress = 0.154) (Fig. 4). Larger parcel size (ha), sugarbush size (ha), non-productive area size (ha), and ecologically significant treatment area (ESTA) size (ha), along with higher overall parcel tap count and percent of the top three reported overstory species in non-sugar or red maple (*Acer rubrum*) (%) were located in the portion of the ordination space occupied by Large production parcels (Fig. 4), whereas greater total basal area (m^2/ha), average tap count (/ha), and metric tons of CO_2 stored (t/ha) were associated with Small production parcels in the negative portion. Successive indicator analysis revealed a higher proportion of the top three reported canopy species in sugar maple and higher overall sugarbush basal area were associated with Small production parcels (Table 3). Additionally, larger overall parcel size,

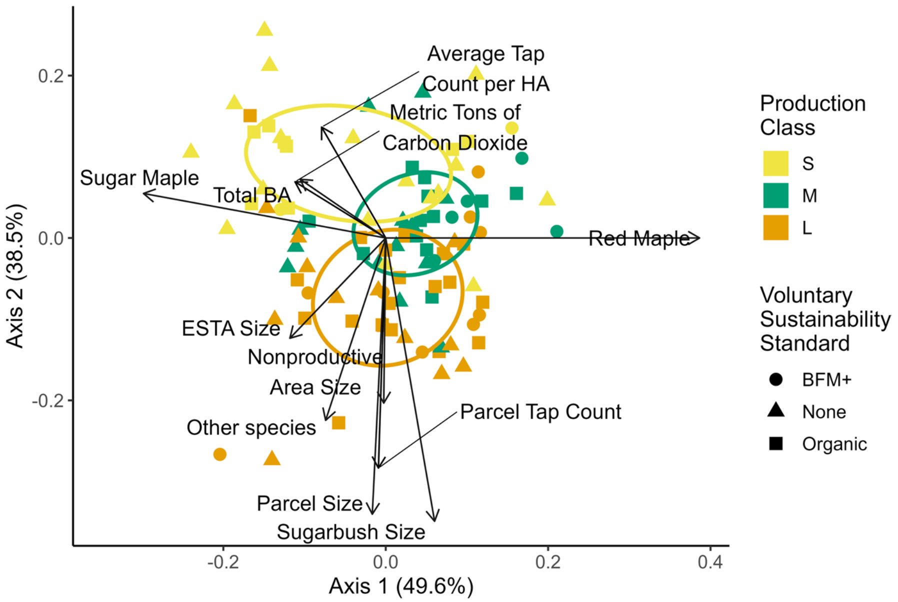

Fig. 4 Non-metric multidimensional scaling ordination showing significant parcel and forest composition attributes in UVA program enrolled sugarbushes. Points represent the size of parcel attributes and average forest composition for sugarbushes at the parcel level. Biplot vectors display significant parcel attributes, forest composition elements, and tapping information with substantial ($\alpha=0.05$) correlations with the main axes. Small (S) production sugarbushes had 1,000–4,999 taps, Medium (M) had 5,000–9,999 taps, and Large (L) had 10,000 + taps. 'BFM + ' represents sugarbushes both recognized by Audubon's Bird-Friendly program and organic certified. 'None' represents sugarbushes enrolled in Use Value Appraisal (UVA) with no additional certification or recognition. 'Organic' represents sugarbushes with organic certification alone

Table 3 Indicator analysis for all parcels showing significant relationships between sugarbush and parcel attributes and production classes, as well as engagement with VSS

Indicator	Group	P-value
Production Class		
Greater proportion of sugar maple in top three reported overstory species	Small	.034
Higher basal area (m^2/ha)	Small	.003
Higher parcel mapped size (ha)	Large	.001
Higher sugarbush mapped size (ha)	Large	.001
Higher non-productive area mapped size (ha)	Large	.013
Voluntary Sustainability Standard		
Greater proportion of red maple in top three reported overstory species	BFM Recognized + Organic Certified	.008
Greater proportion of sugar maple in top three reported overstory species	No Voluntary Enrollment	.005

sugarbush size, and non-productive area size were strongly associated with Large production parcels. Substantial differences between production classes were corroborated by PER-MANOVA ($F_2 = 11.5$, $p = 0.001$), which indicated all classes as significantly different ($\alpha = 0.05$) from each other. Tests for the homogeneity of multivariate dispersions among the production classes ($F_2 = 3.19$, $p = 0.045$) were significant and subsequent pairwise comparisons found differences in the dispersions of the Small and Medium production classes to violate this assumption. There were marginally significant differences in the average composition of individual parcels based on engagement with VSS ($F_2 = 1.87$, $p = 0.055$), which indicated that parcels holding both BFM recognition and organic certification were ($\alpha = 0.05$) different from those parcels not engaging with VSS. Parcels enrolled solely in UVA and not engaging with additional VSS were associated with a higher proportion of sugar maple in the overstory, while those with more red maple had high fidelity to parcels with both BFM recognition and organic certification based on indicator analysis (Table 3).

Operation Age

There were marked differences in parcel size and configuration, as well as sugarbush structure and composition for sugarbushes with operation age information, as confirmed by PER-MANOVA ($F_1 = 3.08$, $p = 0.016$), indicating sugarbushes tapped before 2010 were significantly different from those tapped in or after 2010 (Fig. 5). Higher total basal area and QMSD had significant fidelity to sugarbushes tapped before 2010 and a higher proportion of non-sugar or red maple as a primary overstory species was associated with sugarbushes tapped in or after 2010 based on indicator analysis (Table 4). There was no influence of engagement with VSS ($F_2 = 1.63$, $p = 0.102$) or its interaction with timing of tapping initiation ($F_2 = 1.50$, $p = 0.128$) on sugarbush structure and composition. Production class influenced

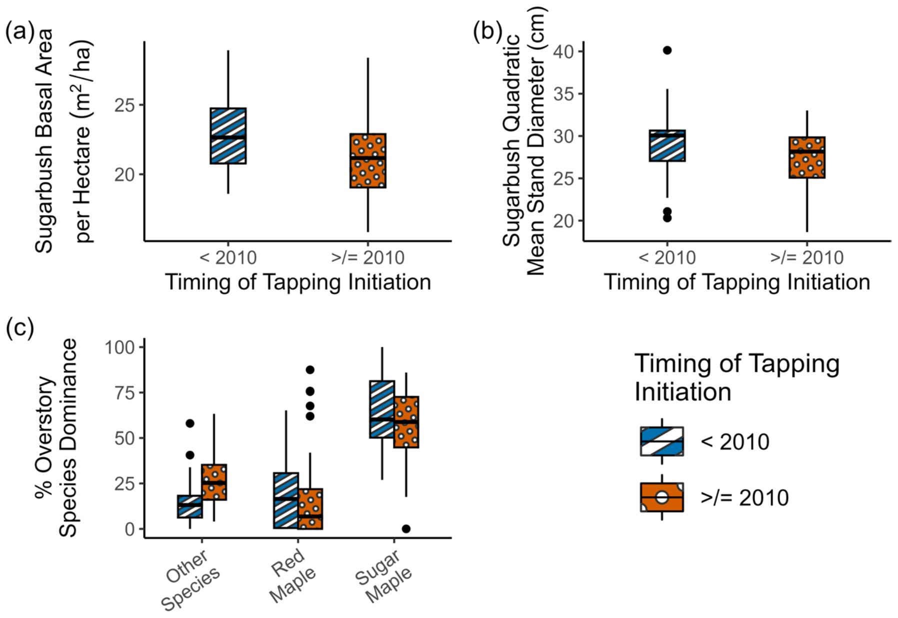

Fig. 5 Comparisons of the structure and composition of sugarbushes tapped before 2010 with those tapped in 2010 or after, including the average **a** sugarbush basal area, **b** mean stand diameter, and **c** overstory composition of the top three reported species

Table 4 Indicator analysis for sugarbushes with operation age information showing significant relationships between sugarbush and parcel attributes based on timing of tapping initiation, as well as production class

Indicator	Group	P-value
Timing of Tapping Initiation		
Higher basal area (m^2/ha)	< 2010	.041
Higher quadratic mean stand diameter (cm)	< 2010	.039
Greater proportion of non-sugar or red maple in top three reported overstory species	≥ 2010	.001
Production Class		
Higher basal area (m^2/ha)	Small	.031
Higher parcel mapped size (ha)	Large	.003
Higher sugarbush mapped size (ha)	Large	.001

sugarbush structure and composition ($F_2 = 5.26$, $p = 0.001$) but did not significantly interact with timing of tapping initiation ($F_2 = 0.71$, $p = 0.697$). Pairwise comparisons showed all production classes to be significantly different from each other and indicator analysis revealed higher total basal area to have high fidelity to Small production parcels, while larger total parcel size and sugarbush size were associated with Large production parcels (Table 4). There was no significant difference (X^2 (2, n = 67) = 3, $p = 0.200$) in the number of sugarbushes tapped before 2010 and in or after 2010 by production class, nor between those with organic certification and no certification (X^2 (1, n = 67) = 0.3, $p = 0.600$).

Management Activities

For analysis, management activities were condensed into four categories. No activity was scheduled for at least one sugarbush stand for 59% of parcels. Likewise stand tending treatments were assigned to at least one sugarbush stand for 44% of parcels, regeneration treatments for 20%, and NNIS treatments for 12%. Comparisons of the above treatment categories across productions classes using a PER-MANOVA ($F_2=3.378$, $p=0.021$) found Large production sugarbushes to be significantly different from Small and Medium (Fig. 6). Indicator analysis revealed a higher percentage of sugarbush area with no activity scheduled to be strongly associated ($p=0.005$) with Large production sugarbushes. No significant differences in scheduled management activities based on engagement with VSS ($F_2=0.306$, $p=0.874$) were observed. A similar analysis was conducted on the reduced data set containing information on tapping initiation (Fig. 6). Scheduled management activities between

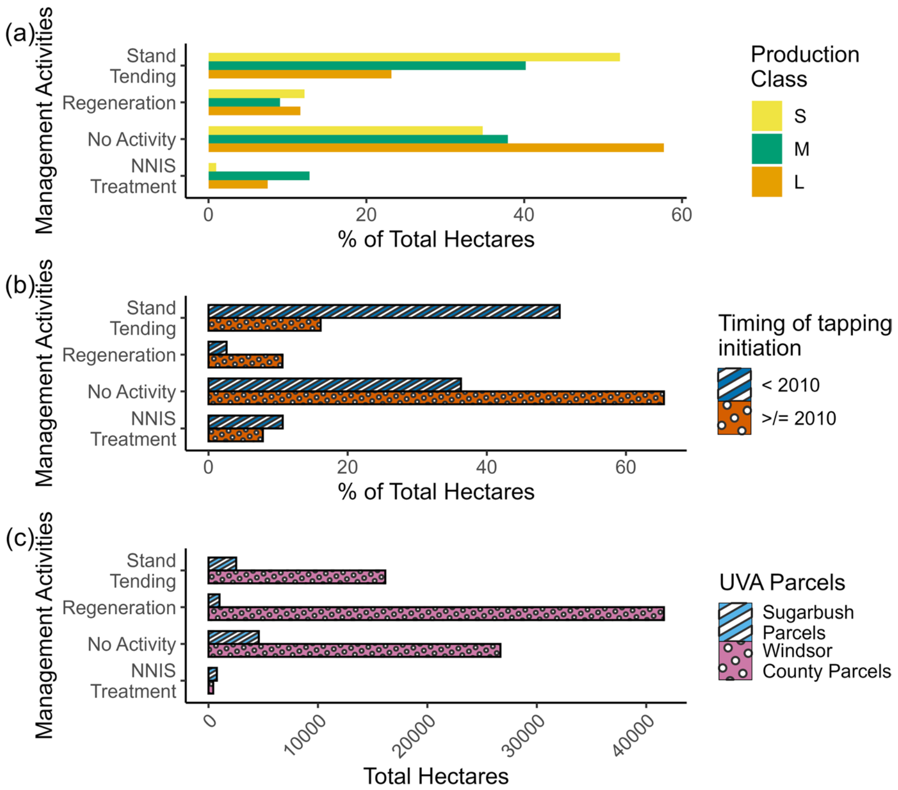

Fig. 6 Management activities scheduled for the next 10 years as a proportion of total sugarbush hectares among **a** production classes and **b** operation age, as well as the total hectares scheduled by management activity **c** between sugarbushes in this study and all Use Value Appraisal (UVA) enrolled forest parcels in Windsor county, VT (Nevins 2019). Small (S) production sugarbushes had 1,000–4,999 taps, Medium (M) had 5,000–9,999 taps, and Large (L) had 10,000 + taps

parcels with stands tapped before 2010 and in or after 2010 showed no significant differences (F_1 = 0.379, p = 0.672) when tested alone or when interacting with production class (F_2 = 1.49, p = 0.210) or VSS engagement (F_2 = 0.332, p = 0.860). Comparisons of total hectares scheduled per management activity group for sugarbushes in the sample, excluding those from Windsor county, with a 2017 assessment of scheduled management activities for forest parcels enrolled in UVA in Windsor county, VT (Nevins 2019) found no significant difference (Kolmogorov-Sminov test, D (4) = 0.75, p = 0.229; Fig. 6).

Discussion

All sugarbushes assessed in the study were enrolled in the UVA program and more than half had organic certification or BFM recognition and organic certification. Despite all programs requiring 25% of the sugarbush overstory to be in non-sugar maple species, parcels engaging with VSS met this benchmark at much higher rates. Parcels below the 25% requirement can still be enrolled in any of these programs, requiring a plan to increase species diversity over time (VT Fpr 2015; VOF 2024; Audubon Vermont (n.d.). Sugarbushes with BFM recognition and organic certification also had a greater proportion of red maple in their canopies. Although VSS engagement and species diversity are only correlated, it may indicate that producers more aligned with VSS are more likely to enroll and/or that the additional management standards and oversight created by VSS have an influence on management decision-making. However, this study did not assess sugarbush composition and management pre- and post-enrollment, nor did it solicit reasons for enrollment and management decision making from sugar makers. The positive relationship between VSS engagement and diversity benchmarks may also reflect the economic advantages of VSS in the marketplace, which benefit producers and their operations, again impacting decision-making. Economic premiums for organic and fair-trade certified products and greater financial security for producers have been documented for other NTFPs (Duchelle et al. 2014; Girma and Gardebroek 2015).

Organic certification of maple has taken place in VT for over 25 years (Pierce et al. 2008). The cost of organic certification in the US can be as low as a few hundred dollars and as high as several thousand, depending on the structure and size of the operation to be certified and the practices of the certifier (e.g., MOFGA 2024; CCOF 2025). There are fees for the initial application and annual renewals, as well as assessments and inspections. The bulk sale price of organic maple syrup is estimated to be 5–10% higher than conventionally produced syrup (Wheeler et al. 2022). It is therefore no surprise that Large operations are more likely than Small to be organic certified, with its attendant costs and potential for higher premiums. As Large operations occupied more land in our study and account for a much greater proportion of sap production in VT (USDA Nass 2024b), their higher rates of organic certification may have outsized effects for sugarbush management and health, especially where species diversity is concerned. In 2019, it was estimated that 1.7 million gallons of organic syrup were produced in VT, which would account for approximately 83.7% of VT's total crop that year (USDA Nass 2019;

2020), although this estimate may be high. Means to increase access to certification schemes for small producers include producer cooperatives and contract sale to a processor or exporter who oversees certification, including costs (Le Courtois et al. 2011; Girma and Gardebroek 2015). Certification success relies on stable or growing demand for organic products and cost-share programs may be an effective means to lower barriers to enrollment for smaller producers (Whelan et al. 2024).

More recent updates to sugarbush management guidance, which encourage the avoidance of sugar maple monocultures and the retention of stand-level tree species diversity to reduce the likelihood of insect outbreaks (Chapeskie et al. 2006; Parker et al. 2013; Hagenbuch et al. 2025), may be reflected in the differences exhibited between more recently tapped sugarbushes (in or after 2010) and those with longer histories of sap production (before 2010) in our study. Newer sugarbushes contained greater non-maple species diversity while older sugarbushes had larger trees and higher stocking; conditions that may also support greater aboveground carbon stocks (Jevon et al. 2019) and species associated with large-tree structures (Paillet et al. 2017). The management history of these more recently developed sugarbushes is unknown, however, it is possible that prior management focused on promoting other forest products, which may have encouraged diverse species retention. It seems unlikely that producers would preferentially tap stands with more marginal maple composition, although estimates of sugarbush availability in VT vary (e.g., Farrell 2012; Matthews and Iverson 2017). Changes in sap collection and processing may facilitate tapping in more diverse stands, including those with greater red maple composition. Other factors which impact tapping initiation and sugarbush expansion, like ownership and proximity to current sugarbush infrastructure, were not examined in our analysis. We also found that the average density of taps per hectare within the sugarbush did not vary substantially with production size, potentially indicating that tapping density is more a function of forest structure and composition (i.e., available number of maples of adequate size) than it is of operation size. This idea is also reflected by the association between Large production sugarbushes and larger parcel and sugarbush size, along with their utilization of a greater proportion of the total parcel for tapping than Small. Similar tap density across production classes may also indicate that managers target stands with a specific minimum density of potential taps available for utilization as sugarbushes, although the positive relationship between tree size and sap yield indicates that not all taps produce equally (Isselhardt et al. 2018).

Although overstory species diversity is a long-standing and integral part of the stand description of a FMP, inclusion of the status of biological legacies (e.g., snags, downed woody material) and criteria to maintain or increase their presence is a more recent addition. The BFM program had the most developed standards for legacies, however, their overall inclusion in plans was low and plans for BFM recognized sugarbushes did not include snag targets at higher rates. BFM participants are given one year from the time of enrollment to update or amend their plans to meet program standards, which may have contributed to this result (Hagenbuch, personal communication, January 22, 2025). Another factor may be the more recent creation of this program, which is not as established as organic certification nor is it third-party verified at this time, and current lack of associated financial premium. As organic certified products have an established market and command price premiums, standards required for accreditation may have a stronger influence than those without, such as BFM. Furthermore, targets for biological legacy maintenance and creation are not required by the UVA program, which may help to account for their overall low presence in plans. These results suggest that voluntary government standards, represented by the UVA program, influence both what is included and omitted from management plans.

Management recommendations for sugarbushes originally developed from agricultural systems or timber management frameworks (e.g., Smith and Gibbs 1970; Lancaster et al. 1974). Guidance has changed over time, particularly in response to technological innovations in sap collection and processing, however, recommendations to maintain sugarbushes at lower tree densities have persisted given that these conditions encourage wider, deeper crowns and support vigorous, healthy crop trees (Lancaster et al. 1974; Houston et al. 1990; Chapeskie et al. 2006). Despite these recommendations, sugarbushes in our study were more likely to carry a higher stocking relative to levels recommended for timber production, especially for sugarbushes with a longer history (i.e., before 2010) of tapping, showing a movement away from practices designed to boost sap sweetness by sugarbush managers. This higher stocking likely reflects two key differences between sugarbushes and the forest management context for which stocking guidelines were developed. First, tubing is the primary mode of sap collection. The lateral and main lines used for collection are generally replaced only every 10–20 years. As a result, silvicultural activities designed to reduce basal area and encourage tree-level vigor and growth may be viewed as conflicting with the maintenance of this sugarbush infrastructure, given that lines would need to be removed and replaced to facilitate entry by heavy machinery and harvest or thinning activities (Isselhardt et al. 2022). Second, as all maples meeting minimum tapping diameter can provide sap, there may be hesitation to reduce stocking given perceived impacts to overall sap yield, especially as guidance on optimal stocking to balance tree growth and sap yield is insufficient. The lack of scheduled management activities for sugarbushes we observed also supports this assertion. We did not have access to information on whether operations producing syrup used wood, oil or other means to fuel their evaporators, which may also impact the type and frequency of scheduled management activities.

Management plans in our study were written by foresters from more than 30 companies, although almost 40% of plans came from one company. No plan in our sample included a tap yield target. A 2022 survey of foresters working in sugarbushes across the northeast US found that 37% of respondents used no published sugarbush management guide to develop their silvicultural prescriptions (Isselhardt et al.). It is explicit in the UVA program manual that sap production be consistent with sustainable forest management and follow the stocking standards of northern hardwood forests developed for sawtimber management (VT Fpr 2010, 2015). Although there is a wide range of expertise among foresters in developing management plans for sugarbushes, there is a clear need for updated and well-researched guidance for sugarbush silviculture. Ontario sugar makers in an earlier survey expressed a desire for foresters more familiar with the specifics of sugarbush management (Clark and McLeman 2012). This indicates there is room for growth not only in the development of sugarbush silviculture, but also in the training of those who may implement it. The unique nature of annual sap production and the relatively long time needed to develop a stand ready for tapping makes the study of silvicultural approaches to sugarbush management challenging and helps to explain the gap in science-based knowledge around modern production practices and forest management.

There is considerable overlap between the principles of ecological forestry and recently developed best management practices (BMPs) for promoting sugarbush health and biodiversity (Hagenbuch et al. 2025). For example, these BMPs encourage targeted regeneration within the sugarbush, promote retention or enhancement of vegetative diversity across canopy layers, and control of NNIS, consistent with the principle of complexity and diversity (D'Amato and Palik 2021). Likewise, recommendations for maintaining and recruiting snags and downed logs reflect the principle of continuity and associated biodiversity values. Collectively, these BMPs and their ecological benefits can be accomplished through a variety of multi-aged silvicultural approaches that follow these principles, while also specifically promoting health and vigor of overstory maples to maintain higher growth rates, vigor, and subsequent sap yields and tapping sustainability (van den Berg et al. 2016; Smallidge et al. 2022). The combination of high stocking and limited planned silvicultural activity in the plans we evaluated contrasts with these recommendations and may represent greater vulnerability to changing climatic conditions, as well as lower biodiversity benefits and sap yields. Although the range in site and forest conditions across sugarbushes necessitates a degree of flexibility in management approaches, foresters should strive to integrate these BMPs and considerations for maple crop-tree health to advance the sustainability of sugarbush stewardship. To increase integration with other management goals, future guidance for sugarbushes should move to a per area basis rather than per tap.

Overall, it appears that VSS, especially those that provide financial incentives and increased market access, can contribute to sustainable management in sugarbushes, impacting a large proportion of the sugaring land base in Vermont. Species diversity was a top concern for all programs analyzed in this study, with clear differences based on VSS engagement. This agrees with previous work where 35% of surveyed foresters with experience in sugarbush management in the northeast cited species diversity as a top concern (Isselhardt et al. 2022). As all parcels were enrolled in UVA, it is harder to discern the influence of program enrollment where VSS and voluntary government program standards diverge. Engagement with VSS varied by operation size, illustrating potential barriers to certification for smaller producers. If overcome, increased enrollment for smaller operations could provide yet more biodiversity benefits, as well as economic advantages to producers. Differences in sugarbush structure and composition based on operation age may capture changes in management approaches based on new information and developments in sap collection and processing. Although, across the board, sugarbushes in this study carried high stocking, which may increase their vulnerability, especially given the novel stressors and altered sugaring season presented by global climate change (Matthews and Iverson 2017; Janowiak et al. 2018).

Conclusion

Maple sap is a distinct NTFP with ecological, economic, and cultural significance. Forests managed to sustainably produce maple sap and syrup require unique approaches to support forest health, financial stability, and community wellbeing. Maintenance and promotion of a diversity of tree species and sizes within the sugarbush can be challenging to integrate with some operational aspects of sap production, including minimum tapable tree size and sap collection infrastructure. VSS can provide valuable metrics and incentives to promote biodiverse conditions, which, as evidenced by their adoption by Large maple operations in this study, can lead to benefits at larger scales. Beyond maple production, these findings suggest the potential positive effect of VSS and updated management guidance on biodiversity and sustainability in NTFP production. Operation size also played a role in VSS engagement, highlighting the need for alternate approaches, like cost-share funding, to reach smaller producers. Without access to information concerning sugarbushes not participating in voluntary programs, our understanding of their effect is incomplete. Furthermore, FMPs focus on planned, rather than implemented, management, again limiting our knowledge of the size, frequency, and approaches used in sugarbush silviculture. Given management for maple sap has been taking place for centuries, approaches to sugarbush silviculture and climate adaptation would benefit from further collaboration with Indigenous methodologies and perspectives to co-create sustainable and reciprocal sugarbush stewardship into the future (cf. Ahmed et al. 2023; Patterson et al. 2023). It is clear that silvicultural approaches meeting the contemporary needs of sugarbush managers are underdeveloped at this time. There is a need for relevant and updated management guides, along with foresters trained to implement this guidance within the unique operational context of a sugarbush.

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Data Availability Data is available from the corresponding author on request.

Declarations

Competing interests The authors declare no competing interests.

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