



# Extending Our Scientific Reach in Arboreal Ecosystems for Research and Management

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### Specialty section:

This article was submitted to  
Forest Growth,  
a section of the journal  
Frontiers in Forests and Global  
Change

Received: 20 May 2021

Accepted: 04 October 2021

Published: 08 November 2021

### Citation:

Cannon CH, Borchetta C, Anderson DL, Arellano G, Barker M, Charron G, LaMontagne JM, Richards JH, Abercrombie E, Banin LF, Tagle Casapia X, Chen X, Degtjarenko P, Dell JE, Durden D, Guevara Andino JE, Hernández-Gutiérrez R, Hiron AD, Kua C-S, La Vigne H, Leponce M, Lim JY, Lowman M, Marshall AJ, Michaletz ST, Normark BB, Penneys DS, Schneider GF, Strijk JS, Tihamiyu BB, Trammell TLE, Vargas-Rodriguez YL, Weintraub-Leff SR, Lussier Desbiens A and Spenko M (2021) Extending Our Scientific Reach in Arboreal Ecosystems for Research and Management. *Front. For. Glob. Change* 4:712165. doi: 10.3389/ffgc.2021.712165

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The arboreal ecosystem is vitally important to global and local biogeochemical processes, the maintenance of biodiversity in natural systems, and human health in urban environments. The ability to collect samples, observations, and data to conduct meaningful scientific research is similarly vital. The primary methods and modes of access remain limited and difficult. In an online survey, canopy researchers ( $n = 219$ ) reported a range of challenges in obtaining adequate samples, including ~10% who found it impossible to procure what they needed. Currently, these samples are collected using a combination of four primary methods: (1) sampling from the

ground; (2) tree climbing; (3) constructing fixed infrastructure; and (4) using mobile aerial platforms, primarily rotorcraft drones. An important distinction between instantaneous and continuous sampling was identified, allowing more targeted engineering and development strategies. The combination of methods for sampling the arboreal ecosystem provides a range of possibilities and opportunities, particularly in the context of the rapid development of robotics and other engineering advances. In this study, we aim to identify the strategies that would provide the benefits to a broad range of scientists, arborists, and professional climbers and facilitate basic discovery and applied management. Priorities for advancing these efforts are (1) to expand participation, both geographically and professionally; (2) to define 2–3 common needs across the community; (3) to form and motivate focal teams of biologists, tree professionals, and engineers in the development of solutions to these needs; and (4) to establish multidisciplinary communication platforms to share information about innovations and opportunities for studying arboreal ecosystems.

**Keywords:** canopy crane, tree climbing, robotics, epiphytic, tree canopy, canopy access, canopy biology, drones (UAV)

## INTRODUCTION

The arboreal ecosystem is a critical terrestrial environment, fundamental to global carbon, water, and nutrient cycles (Barker and Becker, 1995; Bassow and Bazzaz, 1997; Santiago et al., 2004) and biodiversity maintenance (Ozanne et al., 2003; Nitta et al., 2020). Large trees store a substantial proportion of the world's terrestrial biomass (e.g., Slik et al., 2013) and forested ecosystems contain nearly half of all global above-ground biomass, primarily in the form of wood in large trunks and limbs (Chen et al., 2014). Remarkably, more water flows through the stems of plants and the pores of leaves than through the mouths of rivers, in the world's water cycle (Schlesinger and Jasechko, 2014), enough to generate local weather patterns (Makarieva et al., 2014). While the living tissue (cambium, phloem, parenchyma in the sapwood, leaves, buds, and reproductive parts) contributes a small proportion of overall tree biomass, these highly reactive organs represent an immense physiological interface with both the abiotic and biotic environment. Arboreal processes, therefore, have consequences for global biogeochemical, hydrological, and ecological cycles.

Terry Erwin and Janice Scott coined the term “arboreal ecosystem” to capture the vast complexity and importance of the poorly explored above-ground terrestrial environment created by trees (Erwin and Scott, 1980; Erwin, 1982). They identified it as a last frontier for terrestrial biodiversity research. Arboreal ecosystems span the planet and scale in density and structure, from complex multi-layered tropical rainforest to lone urban street trees. The structural complexity of the canopy is a useful proxy for habitat richness and correlates with the biodiversity of dependent taxa (e.g., Gouveia et al., 2014). Structural complexity, in turn, is correlated with canopy height and environmental factors, with the highest complexity found in evergreen tropical rainforests (Ehbrecht et al., 2021) where trees commonly exceed 70 m (Banin et al., 2012; Shenkin et al., 2019).

Arboreal structure influences and is influenced by microclimate, which includes irradiance, temperature, humidity and carbon dioxide concentrations, and is highly dynamic across space and time (Davies-Colley et al., 2000; Newmark, 2001). In temperate zones, bud burst and the initiation of growth after months of winter dormancy occurs over several days, coordinated with local weather patterns. In forests around the world, large synchronous pulses of seed production by plant populations, known as mast events, occur at irregular intervals across years (Kelly and Sork, 2002; Pearse et al., 2020). The many important plant biotic interactions in the arboreal environments include herbivory (Lowman, 2001), pollination (van Dulmen, 2001; Kettle et al., 2011), seed dispersal (Seidler and Plotkin, 2006; Jordano et al., 2007), and seed predation (Janzen, 1971). These interactions can occur on short time scales and early detection can be important for management decisions. Detailed observation and sampling are important for understanding mature tree biology and for identifying critical canopy traits and functions that determine trees' vulnerabilities to environmentally driven decline (McDowell et al., 2018).

Our ability to understand canopy-dwelling organisms also depends on how we access the arboreal ecosystem, because spatial distribution of canopy-dwelling organisms is inherently three-dimensional. Sedentary and mobile organisms partition themselves vertically according to microclimatic and biotic gradients from the forest floor to the canopy (Petter et al., 2016; Oliveira and Scheffers, 2019), as well as laterally within the canopy from within the trunk to the surface of peripheral branches (Volf et al., 2019). Fine-scale environmental conditions are especially important for sedentary organisms such as epiphytes (Zotz, 2007; Petter et al., 2016) and lichens as well as for organisms with specific niche requirements (Dial et al., 2006). An ability to collect samples *in situ* and to monitor

growth and behavior would greatly contribute to our understanding of the evolution, maintenance, and management of terrestrial biodiversity.

Trees are also immensely important to humans living in cities, as a major component of green infrastructure in the built environment. Trees improve human health (Kardan et al., 2015), help us recover from surgery (Ulrich, 1984), clean the air we breathe (Nowak et al., 2014), and provide numerous other benefits (Turner-Skoff and Cavender, 2019). However, trees in the built environment face several novel challenges. Tree care professionals must monitor tree health and vigor to diagnose pests and diseases and assess the risk of structural failure. The built environment is also capable of harboring a surprising amount of biodiversity and biotic interactions (Trammell et al., 2020) and basic research can help translate the rules of life into cities (Langen et al., 2021).

Little is known about how adult trees balance investments in secondary metabolites against herbivores and resource acquisition. Most study of plant functional traits is limited to seedlings and saplings, which often do not scale to the mature tree (Falster et al., 2018). For example, the abundance and diversity of secondary metabolites appears to be greatest during early developmental phases in plants (Coley and Barone, 1996; Endara et al., 2017; Sedio, 2017). A serious gap exists in our knowledge of how resource acquisition and defensive traits against herbivores and pathogens change across space and time (Barton and Boege, 2017). Collecting leaves for trait mapping, molecular and DNA analyses, species identification and new species discovery remains a challenge, especially in hyperdiverse tropical forest ecosystems. Difficulties of collecting any biotic material from the canopy in such systems delays the advance of our knowledge and development of conservation action to preserve them, as well as the systems they inhabit.

To better understand these arboreal processes, we need more fine-grained data. Canopy research is an active field that supports an international community of researchers (Nadkarni et al., 1996, 2011) but our ability to easily and precisely access the many different dimensions of the arboreal ecosystem remains limited. Even with advanced training and equipment, obtaining the necessary observations and samples with the desired speed and precision presents many practical difficulties. These logistical challenges range from accessing terminal branches and twigs with precision and control to working in remote settings far away from roads, networks, and power sources. To better understand this key habitat, we need new methods that can adequately capture rapid changes in canopy structure, vegetative, and reproductive traits, microhabitat, and microclimate through repeated measurements, across seasons and years. In this paper, we bring together a multidisciplinary, international perspective that includes biologists, tree-care professionals, and engineers to (1) collate existing and proposed access methods for studying the arboreal ecosystem; (2) highlight newly emerging engineering approaches to overcome physical and logistical barriers to accessing tree canopies; and (3) point a way forward to create

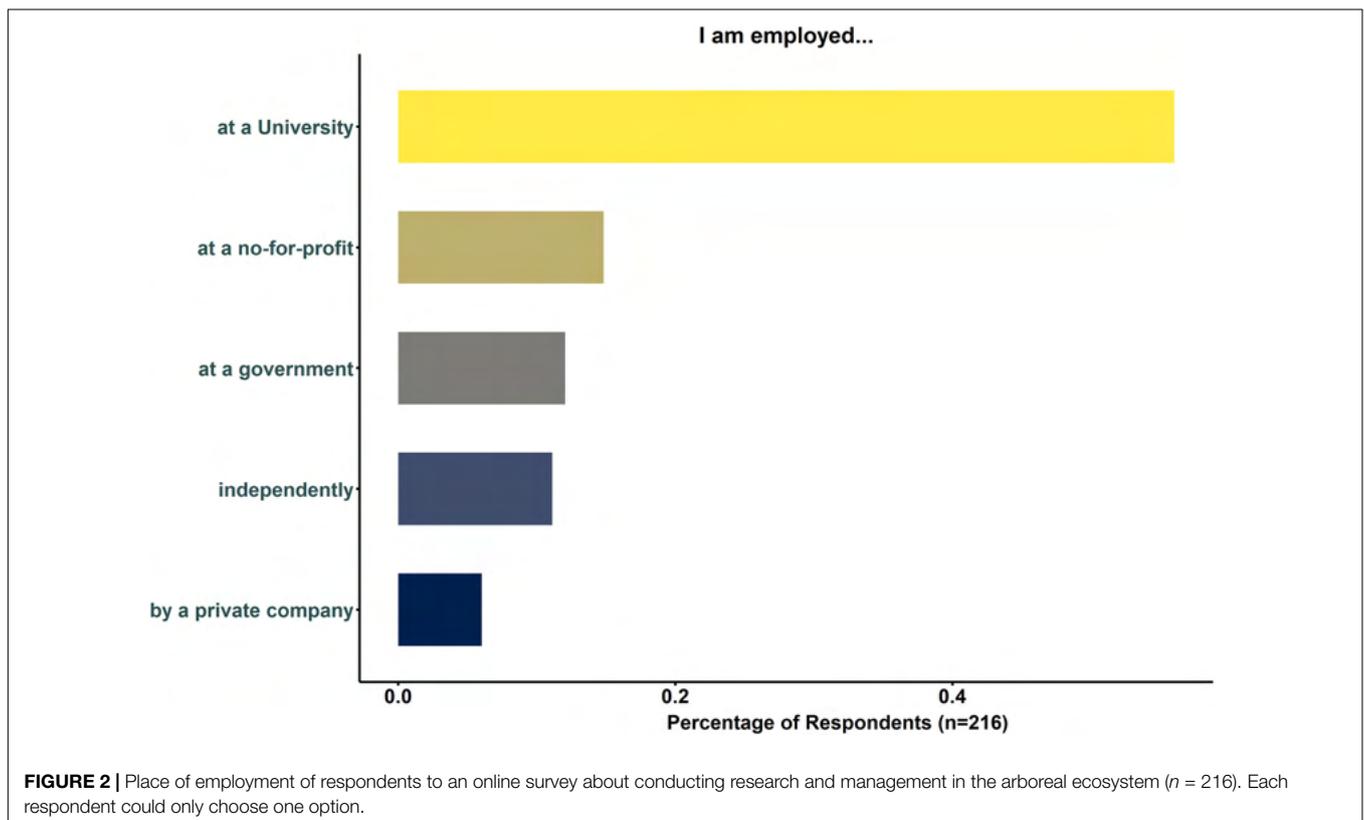
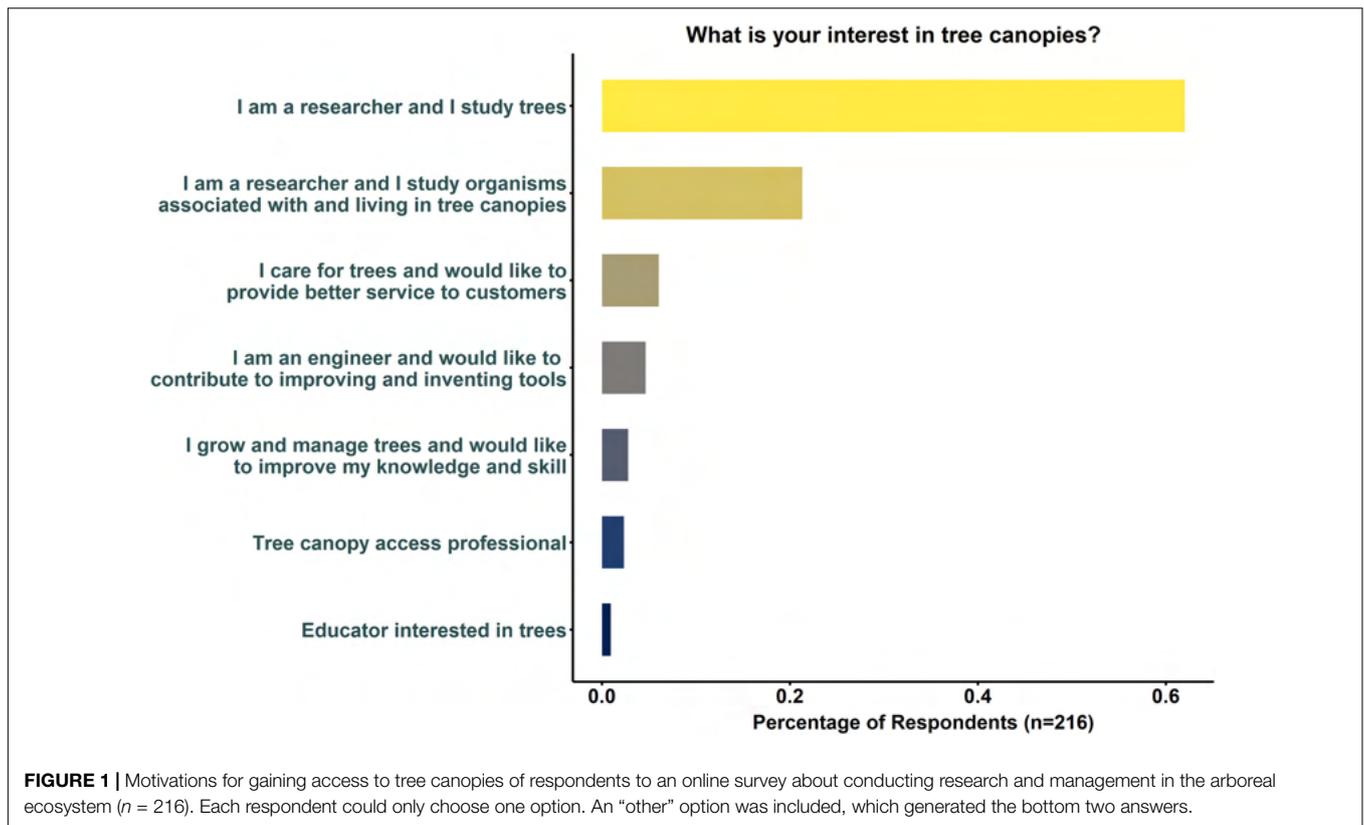
better modes of access for research and monitoring of the arboreal ecosystem.

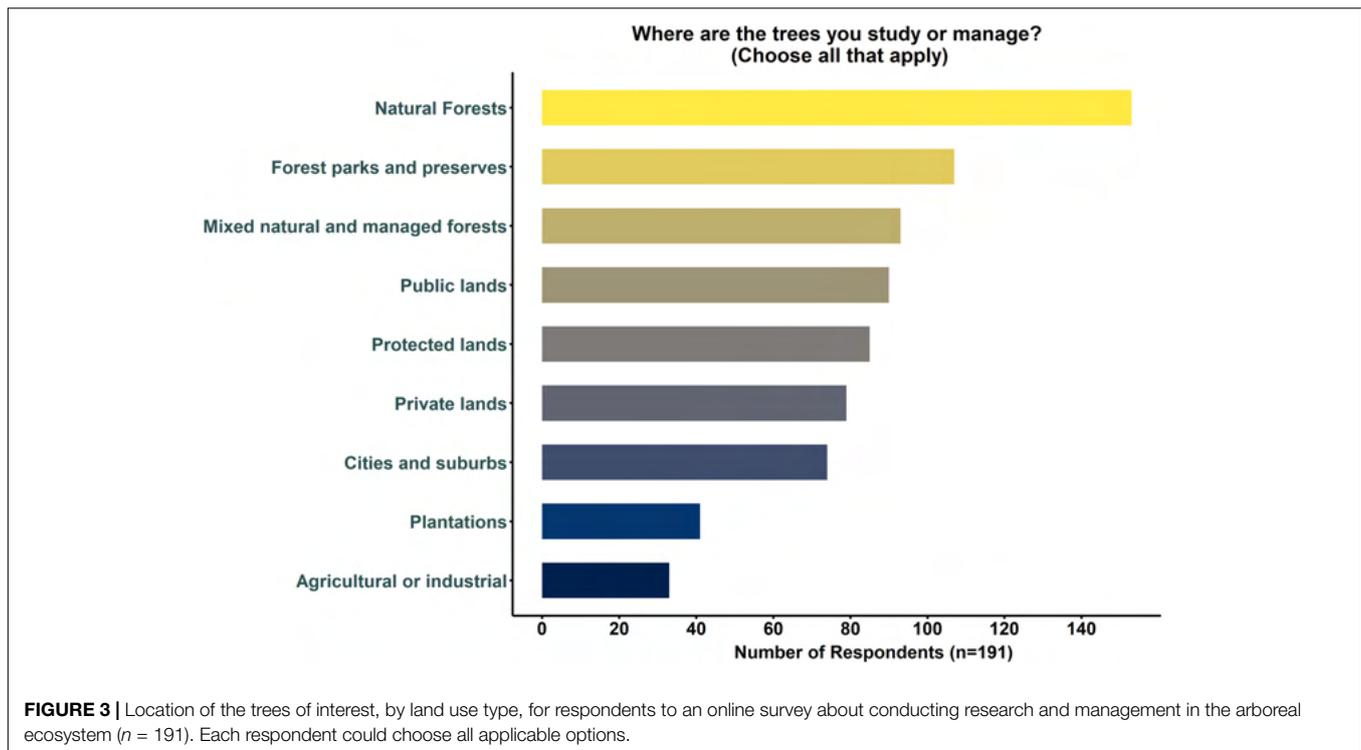
## THE MULTIDISCIPLINARY COMMUNITY SEEKING ACCESS TO THE TREE CANOPY

To assess the current status of methods for accessing tree canopies, we conducted two online surveys from Oct 23, 2020 to Dec 4, 2020. The first survey, with a total of 27 questions, collected basic information about each respondent's current ability and future aspirations for accessing the tree canopy (see **Supplementary Material 1**). Invitations to take the survey were shared through social media platforms, including Twitter, Facebook, and various listservs (e.g., Ecolog, EvolDir, and UrbanForests), and directly with specific groups of interested colleagues, including the now-closed International Canopy Network, staff and collaborators of the Morton Arboretum, and direct messages to specific individuals. In total, 219 people responded, with Ecolog (54), EvolDir (37) and Twitter (26) providing the most completed surveys. Completion of the survey took 7 min on average.

The respondents to the first survey were asked whether they were willing to participate in a subsequent survey and in a continued discussion of how to overcome challenges in tree canopy research. Over three-quarters of the respondents to the first survey (171 or 78%) indicated their interest in participating in the discussion. The second survey was sent only to this smaller group of continuing participants. It contained six open-ended questions designed to gather more detailed information about the specific needs and objectives of the respondents in their tree canopy work (see **Supplementary Material 2**). We received 51 responses (28% of the short list), and average time to completion was 15 min. Additionally, we held two virtual workshops with the respondents eager to continue their participation in a community discussion. This manuscript and plans for further community development are a result of the virtual discussions, both synchronous and asynchronous, that emerged from the workshops.

Most of the responses (**Figure 1**) were from researchers who either study trees directly ( $n = 130$  of 216 total; 60%) or study biotic or abiotic elements of the canopy environment ( $n = 40$ ; 19%), while a smaller fraction manage or care for trees ( $n = 13$ ; 6%). Respondents with an engineering background were in the minority ( $n = 7$ ; 5%) with the distribution of the survey biased toward biologists and arborists. Most respondents worked at universities (**Figure 2**;  $n = 121$ ; 56%), while non-profits, government agencies, and self-employment were all roughly equally represented ( $n = 32, 26, 24$ , respectively). A smaller proportion worked for private companies ( $n = 13$ ; 6%). Additionally, most respondents were affiliated with institutions in the United States ( $n = 134$  of 209 total; 64%) followed by Germany, Mexico, and France ( $n = 11, 8, 8$ , respectively). The trees of interest to the community are found across most land use types (**Figure 3**); although the greatest fraction is found in natural forests and parks and preserves, a substantial proportion





occur on private land, in urban areas, and as part of agroforestry production systems. The trees of interest also span a broad range of vegetation types and seasonal precipitation, with increasing trends toward broadleaved wet forests from temperate to tropical regions (Figure 4).

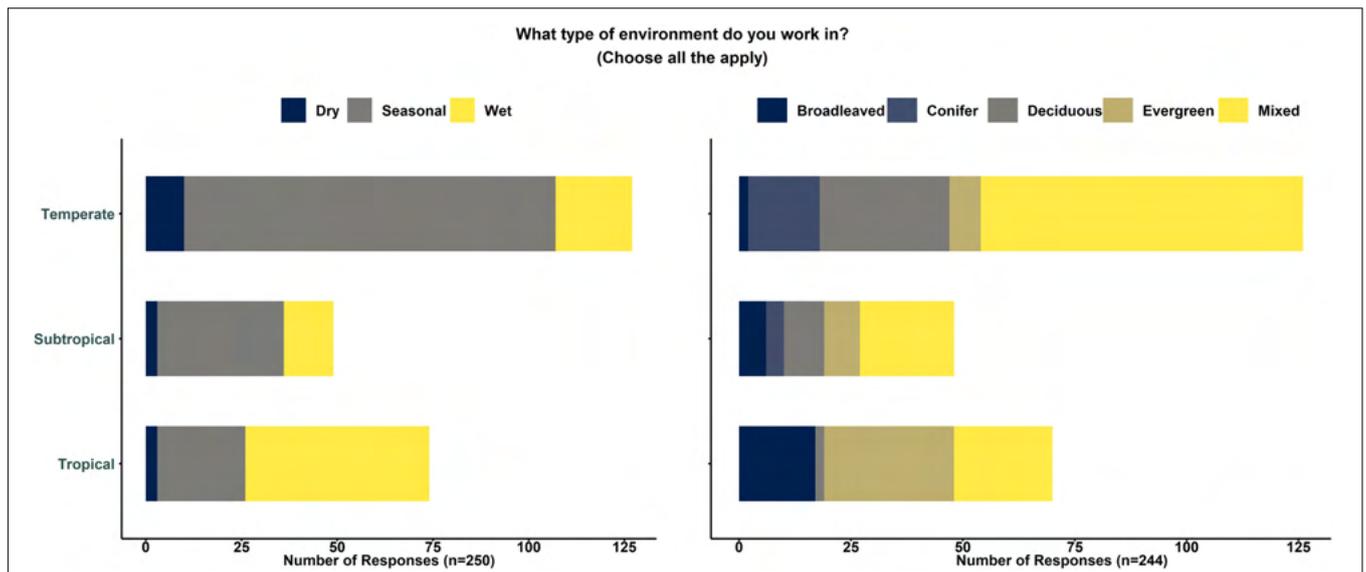
Overall, the respondents indicated that their access to the tree canopy is constrained (Figure 5). When asked directly whether they felt their access was limited, the median score was 64 out of 100, with higher scores reflecting greater agreement (Figure 5A). Some respondents indicated that they were completely unable to get the samples needed to conduct their research (Figure 5B) and the median was 49 out of 100. Additionally, the tool used to collect the sample often has an impact on which sample was selected (Figure 5C—median of 58 out of 100), further limiting the power of the possible research conducted in the canopy. Finally, there was overwhelming agreement that accessing the canopy took too much time (Figure 5D—median of 66 out of 100) and that time is an important consideration (Figure 5E). The strongest indicator that the researcher requires better access to the tree canopy is apparent when a comparison is made between how often respondents currently access the canopy and how often they would, given an effective and useful tool were available (Figure 6). Clearly, we need better tools to study the tree canopy.

## HISTORICAL AND CURRENT APPROACHES TO CANOPY ACCESS

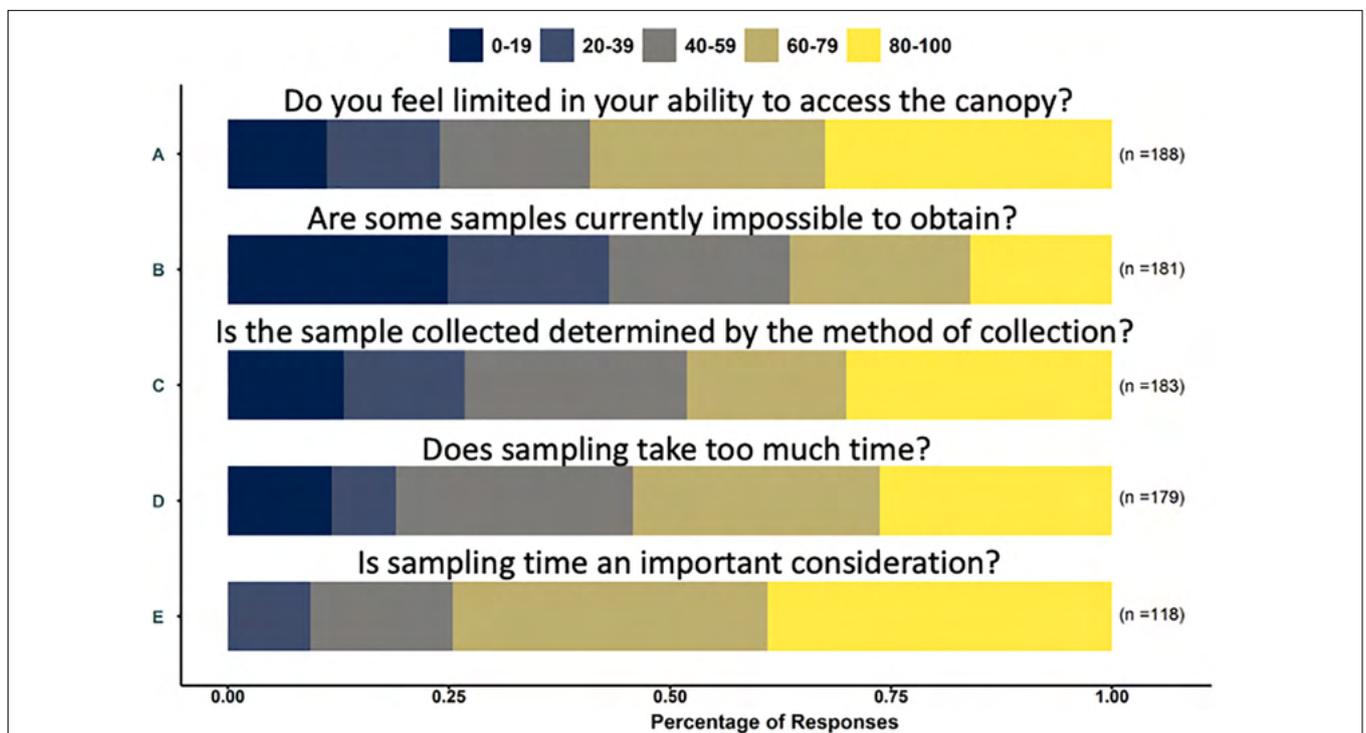
The earliest examples of accessing the canopy for research involve the use of local climbers (Wallace, 1869), felling

trees (Beccari, 1904), and the construction of elaborate hoist systems (Perry, 1978; Perry and Williams, 1981; Mitchell, 1986). E.J.H. Corner famously trained pig-tailed macaques to collect samples in Malaya (Taylor, 2019) but the approach was impractical and was abandoned (Corner, 2013). Rope-based climbing methods have been a mainstay for canopy access because the equipment is relatively inexpensive and portable (Barker, 2002; Anderson et al., 2015, 2020; Falen Horna and Honorio Coronado, 2018). Cranes, towers, walkways, temporary platforms (Kettle et al., 2011), and even dirigibles have been used to create a stable infrastructure from which people can access the canopy. Researchers gather arboreal samples from the ground by using shotguns, slingshots, throwlines, and fogging entire trees. More recently, Unmanned Aerial Vehicles (UAVs) have created a new avenue to gain a close look and even collect samples from trees. Some of these achievements have been reviewed and celebrated (Mitchell, 1986; Moffett, 1993; Parker et al., 1995; Mitchell et al., 2002; Lowman et al., 2012), stimulating important research initiatives focused on the arboreal ecosystem and the continued improvement of our ability to access the canopy.

In our study, we asked respondents in two online surveys to indicate how they gathered samples from the arboreal environment (in the first survey as multiple choices from an itemized list, including an “other” text option; in the second survey as a free text response). To simplify further discussion, the word “sample” is used interchangeably for the remainder of the article for any type of physical sample, digital image, or measurement data that could be collected. After compiling the results, we categorized these methods for access (Figure 7)



**FIGURE 4 |** Climate and type of forest where respondents work. Each respondent could choose all applicable options in an online survey about conducting research and management in the arboreal ecosystem.

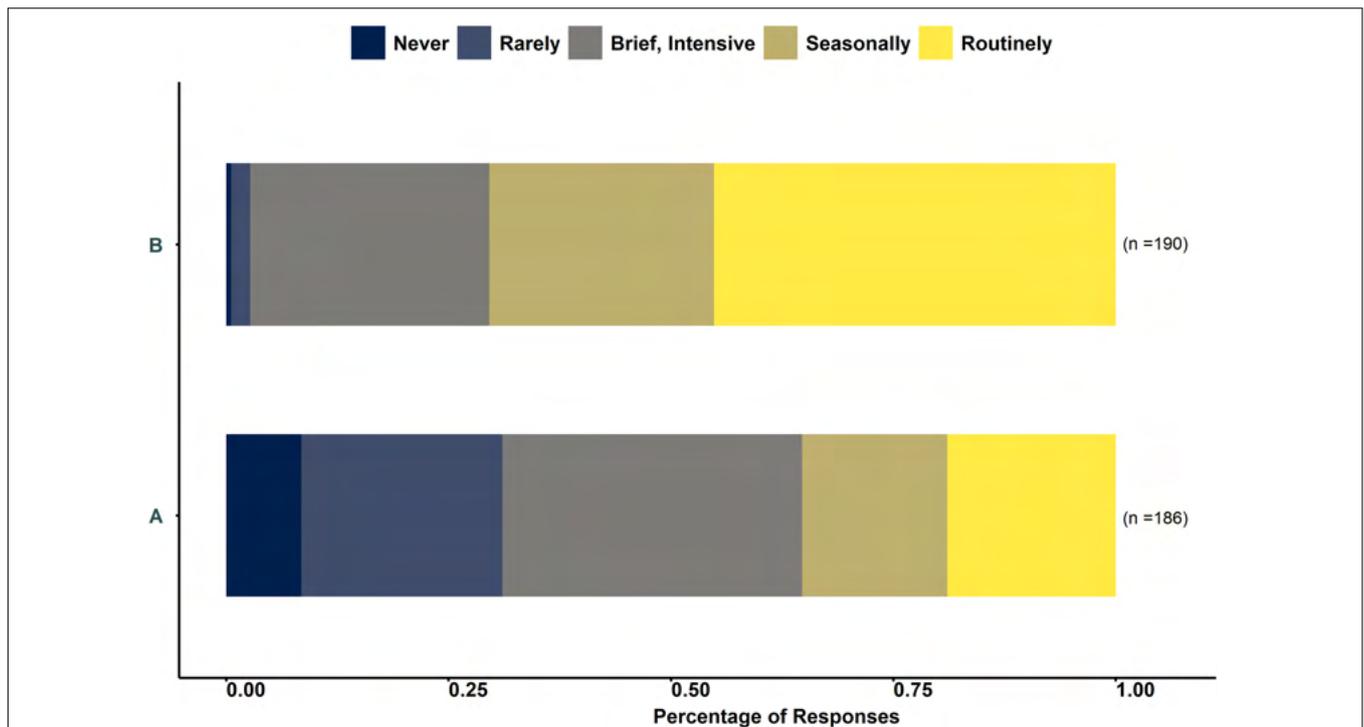


**FIGURE 5 |** Responses to questions about current ability to access tree canopies from respondents in an online survey about conducting research and management in the arboreal ecosystem. Questions were: **(A)** Do you feel limited in your ability to access the canopy? **(B)** Are some samples currently impossible to obtain? **(C)** Is the sample collected determined by the method of collection? **(D)** Does sampling take too much time? **(E)** Is sampling time an important consideration? Respondents expressed their agreement with the question by choosing a number between zero and 100, with 100 being total agreement.

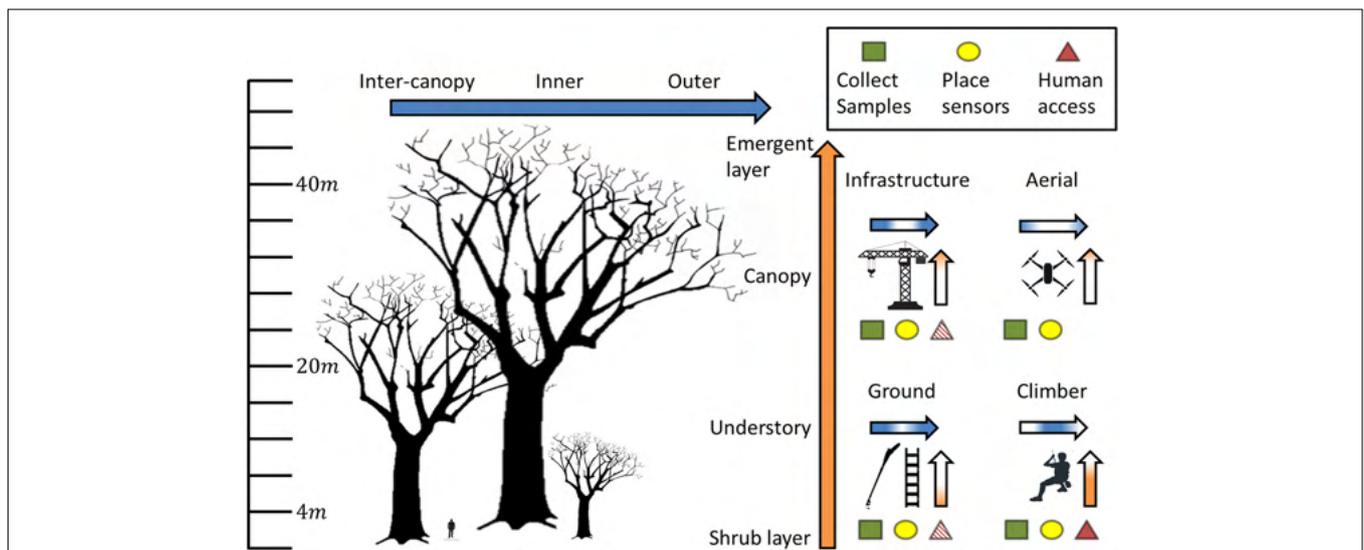
based on “how?” and “when?”. How the sample was obtained included: (1) from the ground, (2) climbing the tree, (3) using infrastructure, or (4) piloting an UAV. Sampling frequency included instantly in a single sampling event or continuously over

some period of time. Here, we summarize the results of these surveys according to this classification system.

Our respondents mostly gained canopy access from the ground, with a third (128 out of 384 total answers) indicating



**FIGURE 6 |** Frequency of tree canopy access reported by respondents given (A) their current methods of access and (B) their desired level of access, if sampling were quick and effective.



**FIGURE 7 |** The relative ability of each of the predominant methods of tree canopy access to obtain a sample, given the sample's position in the tree canopy. The blue shading indicates the horizontal accessibility, from the spaces between tree crowns, the inner crown and the outer crown, left to right. The orange shading indicates the vertical accessibility, from the ground to the emergent portion of the canopy. Shading on horizontal and vertical arrows indicates current access, given each method: darker indicated better access. The modes of sample collection are also shown: instantaneous (collecting a sample) by a square; continuous (place a sensor) by an ellipse; and direct human action by a triangle. Darker shading indicates the overall accessibility by that particular mode.

that they either used some type of slingshot or shotgun to knock down a sample or they simply searched and picked up samples directly from the ground, which are often dropped by animals as they forage. While this method is fast and easy, it greatly limits

the researcher's ability to objectively choose samples. Generally, imprecision and inability to select the exact location of a sample is a major limitation and this difficulty increases with greater heights and forest structural complexity. Methods requiring a

long pole to hoist the sampling device into the tree are limited to relatively low heights in the canopy and necessitate transport of long poles through a forest environment, which is difficult. If upper “sunlit” canopy samples are required, the challenge is even more daunting, and sampling is slow and possibly destructive to the canopy matrix. The use of firearms to shoot down samples also involves a certain amount of personal risk, requires adequate safety training, and is not legal or desirable in all locations, especially in the built environment. The use of ropes to pull down branches can cause significant damage to the canopy and unintended injuries to the tree. Hybrid methods exist by which a line is placed in the canopy (possible using climbing or aerial access) so that sampling equipment can be raised and lowered from the ground. These types of access can also cause unintended structural damage to the tree canopy, which may be problematic for long-term studies.

Climbing was the second most frequently used method (105 out of 384 answers). Rope-based access methods [“rope access”—(Jepson, 2000)] have experienced several innovations over the past two decades. New tools and devices (e.g., hybrid climbing systems that employ both mechanical devices and specialized friction knots) have improved climber efficiency and safety and requiring less physical effort and time. Ropes and specialized equipment for climbing trees are widely available commercially, and relatively affordable and portable, allowing sampling even in remote settings. These methods also involve using slingshots and line launchers to secure the initial ropes and lines. Importantly, with adequate training and expertise, samples can often be obtained from all parts of the tree, including delicate branch tips, epiphytes, and even the open spaces between trees (Anderson et al., 2020), although risk and difficulty increase substantially with taller trees with more expansive, complex crowns.

A main limitation of rope-based methods is that specialized training and experience is needed to execute more sophisticated movements and some trees cannot be safely climbed, for example dead snags growing in isolation from living trees that could permit peripheral access. Many tree-climbing activities are also regulated in most countries with respect to safety in the workplace, as this activity exposes operators to the risk of falling from height (Longo et al., 2013). Climbing can also be time consuming and tiring, so ultimately the number of trees climbed, and number of samples gathered within a time frame is constrained. Sampling can also only be performed on structurally sound trees and repeated rope access must be carefully planned to minimize damage (Chavana-Bryant et al., 2019). Finally, rope access can be combined with other methods, allowing vertical and horizontal movement away from cranes, walkways, and towers (see below). When sampling is performed by a human, rope access offers a flexible and effective means for unbiased and replicable sampling in tree canopies.

Construction cranes (Nakamura et al., 2017) and canopy walkways or towers (Lowman and Bourcius, 1995) require the greatest initial investment, but once installed require no further training or specialized equipment other than the assistance of a crane operator. Therefore, they provide access across the widest range of people, considering age and physical ability. Further, they allow ready access to the open spaces between trees. The

physical infrastructure of cranes and walkways cannot reach the interior tree crown, however, limiting access to the outer crown and branch tips without some type of augmentation or sampling device. They also only provide access to a fixed limited number of trees and environments in the immediate vicinity of the crane or walkway. Additionally, sampling from this population of trees must be carefully managed to avoid disturbing or changing the environment, which can affect long-term study results. Because moving platforms through the canopy can cause damage if not done carefully. Other types of infrastructure include bucket trucks and mechanical means of lifting a person into the tree canopy. These tools provide excellent access to the outer canopy but require substantial capital investment and are only applicable when the tree is accessible by road and grows in the open.

Several of the respondents (50 out of 384 answers) use aerial techniques to gain access to the canopy. A small proportion reported use of mobile infrastructure, such as flying balloons or rafts (Hallé et al., 2000; Mitchell et al., 2002; Dorrington, 2005) but these remain expensive, logistically difficult to transport, and unavailable to most scientists. Remote sensing with drones was the most common aerial method used to sample the canopy. Over the past few years, Unmanned Aerial Vehicles (UAVs) have evolved rapidly and been adopted by scientists in a multitude of applications. Declining acquisition costs, increasing reliability, and ease of use have driven demand, while airspace regulators have enacted rules to facilitate low-risk UAV operations. Collecting physical samples with a UAV has also become possible over the past few years. The first devices used cutting blades or knives attached firmly to the UAV through a pole.<sup>1,2</sup> This, however, can create vibrations and destabilizes the UAV when it meets a branch. A critical development was the suspension of the sampling device beneath the drone. This configuration allows stable operations and a greater sampling reach while keeping the UAV at a safe distance from natural obstacles.

New aerial sampling tools were developed by various labs with multiple actuators and a vision system to assist the operator during sample collection (Finžgar et al., 2016; Käslin et al., 2018; Kutia, 2019; Charron et al., 2020). Among the solutions available on the market, the DeLeaves canopy sampling tool (Charron et al., 2020) has now been used by scientists in a number of field experiments (NEON, 2019; Schweiger et al., 2020; Arseneau et al., 2021). This tool allows tree canopy samples to be collected in about 6 min (i.e., from UAV takeoff to return with the sample) and has proven to be effective in a variety of environments and for more than 30 tree species. The approach also removes a substantial amount of direct human risk involved in other methods, when people are climbing, shooting, or being suspended to collect samples. Recent work used the DeLeaves canopy sampling tool on a custom UAV to assist the pilot during sampling. In that system, an RGB-D camera was used to detect

<sup>1</sup>“How Mythbuster Jamie Hyneman Hacked a Drone to Trim His Trees.” *Popular Mechanics*, Popular Mechanics, 14 Nov. 2017, [www.popularmechanics.com/flight/drones/a26102/jamie-hyneman-drone-plants/](http://www.popularmechanics.com/flight/drones/a26102/jamie-hyneman-drone-plants/).

<sup>2</sup>“Sampler Drones for Forestry Research.” *Rausser College of Natural Resources, UC Berkeley*, [nature.berkeley.edu/garbelottowp/?p=1801](http://nature.berkeley.edu/garbelottowp/?p=1801).

and locate suitable branches for sampling before an on-board computer guided the UAV to autonomously collect the selected branches (La Vigne et al., 2021). This assistance significantly reduces the pilot workload and accelerates the sampling process by more than six times.

UAV sampling still has limitations. For example, it is necessary to maintain a safe distance from the top of the tree to avoid any contact with the propellers. This limits sampling to the upper third and the outer edge of a tree. Finally, while battery life has improved, flight time and payload remain limited (e.g., the DJI M300 has a 9 kg max takeoff weight, a 2.7 kg max payload, a 55 min max flight time and a max speed of 23 m/s). However, in practice, the flight time when fully loaded with sensors and sampling equipment is closer to 15 min. For missions of long duration, multiple sets of batteries need to be carried and recharged in the field when possible (e.g., the DJI M300 has a 2.7 kg battery pack of 548 Wh). The noise associated with UAVs may also disrupt organisms inhabiting natural ecosystems. While there are instances of UAVs having been attacked by birds (Yaacoub et al., 2020; Chaari and Al-Maadeed, 2021), which can disrupt research progress and harm birds, best practices have been developed to fly UAVs around birds (Junda et al., 2015). Noise or activity produced may also create other types of unsafe situations for researchers. For instance, the UAV noise may disturb unseen nests of bees or wasps, which in one instance has resulted in the death of a researcher due to bee stings (pers. obs.).

The respondents also pointed out that the site context can also present significant challenges for gaining canopy access. In remote locations, beyond the simple fact that newer technologies require electrical power, complicating their heavy implementation, their noisy operation and high visibility can call attention to researchers working in areas where illegal activities or military conflict are occurring. Developed and populated landscapes, such as cities and towns, present different challenges associated with tree canopy access. While line launching techniques (e.g., slingshot) are used in natural forested areas within cities, they pose considerably more risk in urban forest settings used for recreation, endangering bystanders and property. UAV-based techniques pose additional challenges associated with permission and security concerns in populated landscapes. Finally, sensors or other types of equipment placed within urban tree and forest canopies for continuous or repeated measurements can be stolen or damaged.

## MODES OF ACCESS AND EXPERIMENTAL DESIGN

Beyond the practical details of how the sample is collected, when and where the sample is collected is potentially of even greater importance. Previously, canopy sampling has tended to be arbitrary, non-random, unrepresentative, and opportunistic. Also, low replication or pseudoreplication (*sensu* Hurlbert, 1984) are potential weaknesses. Yet few canopy-based studies report sampling issues (Kapos et al., 1993; Baldocchi and Collineau, 1994; Koch et al., 1994), although logistics and experimental design in arboreal ecosystem research remain undeniably

challenging. But the focus among researchers has shifted from simple access to experimental design and sampling issues (Barker and Pinard, 2001; Bongers, 2001; Nakamura et al., 2017) centered on hypothesis driven quantitative approaches (Rinker and Jarzen, 2004; Volf et al., 2019). Ideally, modes of access and experimental design of arboreal ecosystem research need to be equally rigorous as other terrestrial ecosystem research (Barker and Pinard, 2001; Mitchell, 2001; Sutton, 2001). The quantity and quality of data and samples collected in the canopy should not be compromised based upon how and when the sample can be collected. For example, researchers are not always sufficiently mobile in the upper canopy, so to avoid under- or over-sampling or pseudo-replication, independent replicates can be achieved spatially, by simultaneous sampling by researchers, sensors or traps (e.g., Bassow and Bazzaz, 1997; Bar-Ness et al., 2012) or temporally across days or weeks (e.g., Perez-Salicrup et al., 2001). Devising the best strategies for achieving these comprehensive approaches requires collaboration and coordination across the community of arboreal researchers.

Modes of access and experimental design can vary considerably depending on the aspect of the arboreal ecosystem that is being sampled. For example, the epiphyte community requires capturing the plants living attached to the limbs and branches of a tree. The limited access to the canopy has been calculated to miss, for example, more than 50% of lichen diversity (Boch et al., 2013), much of which is endemic to the upper canopy (Fritz, 2008; Ellis, 2012; Marmor et al., 2013). To study epiphyte communities and obtain complete species lists during inventories, various complementary methods are used, including surveying fallen twigs and branches (Sarmiento Cabral et al., 2015; Gasparyan et al., 2018), using tree pruners (Degtjarenko et al., 2016, 2020), and employing rope-based methods (Fanning et al., 2007; Boch et al., 2013; Kiebacher et al., 2016). Canopy crane access has permitted detailed characterization of epiphyte assemblages across forest strata, but these have been limited to only a few locations (Zotz, 2007; Petter et al., 2016) and gondolas can damage the upper or outer canopy. Trees or branches felled for other purposes or that naturally fall also permit comprehensive sampling of epiphyte diversity (Marmor et al., 2013; Kaufmann et al., 2019). The latter methods are not always applicable in regular surveys or permissible in highly protected forests.

The collection of arthropods and other invertebrates from tree crowns relies on a multitude of sampling methods, including fogging from the ground and insect traps (e.g., Malaise, flight interception, pitfall, sticky traps) that can be lifted with ropes into trees. The integrative IBISCA (Investigating the Biodiversity of Soil and Canopy Arthropods) approach is a good example of the combination of these methods with a wide variety of canopy access tools (e.g., cranes, balloons, rafts, climbers) leading to the development of new sampling protocols (Leponce et al., 2012, 2021). Recent large-scale, multi-taxa projects to access the tree canopy have relied on tree felling, canopy cranes, cherry pickers (Nakamura et al., 2017; Volf et al., 2019; McCaig et al., 2020; Mottl et al., 2020), or ground-level fogging using insecticide (Swart et al., 2020). Canopy-dwelling vertebrates including birds, frogs, lizards, and mammals are commonly studied observationally

either using binoculars, climbing into the canopy, or using remotely sensed images to identify nests (Milne et al., 2021). For more sentient taxa (birds and mammals) and for behavioral studies in particular, there is risk of unintended disturbance or demonic intrusion (Hurlbert, 1984) when researchers introduce themselves into the arboreal environment, thus changing the naturally occurring parameters in the experiment (Barker and Pinard, 2001). Censusing from the canopy accurately captures richness patterns (Anderson, 2009) and can elucidate patterns of vertical stratification (Scheffers et al., 2013). Traps to capture small mammals have been implemented in the canopy and can be installed directly or from the ground (McClearn et al., 1994; Kays, 1999; Lambert et al., 2005).

While methods of access are generally the focus of experimental design, an important distinction about the timing of access was identified in remote discussions among the co-authors, during and after the virtual workshops. Specifically, samples are either collected (1) instantaneously or (2) continuously. Instantaneous samples serve as a snapshot in time, typically involving a physical sample, a measurement, or an image or data taken by cameras or sensors, that is collected a single time without expectations of returning to the site. Continuous samples, on the other hand, can involve either placing a sensor or trap in the tree or repeated measurements of the same part of the tree. These two approaches require fundamentally different techniques and impose different functional constraints on the experimental design. Most methods used by canopy researchers focus on instantaneous sampling, where a physical specimen is removed from the tree. Continuous monitoring and repeated measurements are undergoing a revolution because of advances in sensor technology and camera traps. Sensors have been placed in tree canopies using UAVs (Farinha et al., 2020) and improving upon these methods is one major avenue for innovation. Additionally, repeated sampling of the same tree, preferably even the same part of the canopy, can be necessary during experimental trials or long-term monitoring programs. These repeated measurements often involve the construction of canopy infrastructure but UAVs again might provide a new means of achieving this research. Controlling the structural and physiological impact and logistical burden of these repeated sampling techniques is important aspect to consider (Zandt, 1994).

Remote sensing provides information about forest canopies through a sensor signal resulting from the interaction of electromagnetic energy with the canopy components (Weishampel et al., 1996; Baret and Buis, 2008). The level of detail and type of information obtained from the canopy mostly depends on the type of platform (satellite, airborne, UAV) and sensor (multi/hyperspectral, radar, laser) used. Traditional remote sensing uses satellite imagery and it has improved in terms of the type of sensors, spatial and temporal resolution (Chavana-Bryant et al., 2019; Lechner et al., 2020). UAVs provide relevant canopy information at flexible times, with a higher spatial resolution and a relatively cheaper price when compared to satellite data (Lechner et al., 2020; Dainelli et al., 2021). Arboreal camera traps are effective at capturing photos of canopy vertebrates if foliage is removed from the immediate

vicinity of the camera to prevent false triggering (Di Cerbo and Biancardi, 2013; Gregory et al., 2014; Whitworth et al., 2016; Bowler et al., 2017; Nazir and Kaleem, 2021). Fixed cameras in the canopy as Phenocams or camera traps also provide valuable temporal information to study growth, phenology, harvest traits (Aasen et al., 2020). Ecoacoustic monitoring is an emerging field (Ducretet et al., 2020; Pérez-Granados and Traba, 2021) that could be adapted to canopy research similarly as cameras.

The combination of machine learning techniques with remote sensing data allows several canopy studies ranging from semi and automatic identification and quantification of canopy species using conventional RGB cameras (Tagle Casapia et al., 2019; Ferreira et al., 2020; Wang et al., 2021), multispectral cameras (Gini et al., 2014; Wagner et al., 2020) or hyperspectral sensors (Dalponte et al., 2014), to assess health status (Dainelli et al., 2021), phenology (Feng et al., 2021), above-ground biomass estimation/quantification using RGB, radar or Lidar (Marks et al., 2014; Brede et al., 2019; Dainelli et al., 2021), canopy traits (Thomson et al., 2018; Ganivet and Bloomberg, 2019), or to detect fauna with thermal sensors (Spaan et al., 2019; Zhang et al., 2020). In all the cases, to be most effective, calibration against carefully chosen samples at the top of the canopy is required to provide accurate results (Käslin et al., 2018; Chavana-Bryant et al., 2019; Schweiger et al., 2020). In addition, while we are aware that some high-tech methodologies such as airborne laser-guided imaging spectroscopy could help to solve these issues especially in tropical forests, these methodologies are expensive and not accessible for all researchers (Baraloto et al., 2010; Asner et al., 2017). Thus, setting a workflow that allows drone-based leaf sampling and drone-guided imaging spectroscopy would be valuable in terms of cost reduction and canopy data accessibility.

## ENGINEERING AND ROBOTIC POSSIBILITIES

Given the need for more precise and versatile ways to access the arboreal ecosystem, both for instantaneous sampling and for continuous monitoring, recent progress in robotics can enable new capabilities. Historically, robotics has been used to perform tasks known as “the 3Ds” (typically, dull, dangerous, or dirty, but also sometimes difficult, demeaning, and demanding), particularly repetitive tasks in manufacturing and warehouse fulfillment (Bogue, 2016). Sensors, sometimes located on mobile robots to create deployable and reconfigurable sensor arrays, are also used to monitor certain areas for extended periods of time and in a variety of environmental conditions. Given these examples, one can presume that teleoperated robots could be deployed in the exploration of a tree canopy during an expedition, to address many of the sampling issues discussed above. Automating data collection can also provide solutions to creating large, replicable datasets and collecting repeated measurements. To inspire new ways to perform canopy research, we provide a short review of recent relevant robotics progress and the challenges that remain.

Robots are typically classified either as manipulator arms or mobile robots. Manipulator arms are common in factory

settings, moving objects or performing tasks such as painting or welding. While manipulators may employ different joints and linkages, they are generally similar to each other and could best be deployed along with canopy infrastructure, where a fixed anchor point would be available. For example, when placed on a canopy crane, a manipulator arm could extend the reach and precision of sample collection. Mobile robots have a much more varied form and are typically classified according to their mode of locomotion. These include wheeled, tracked, and legged (or combinations thereof) robots for terrestrial locomotion, and fixed-wing, rotorcraft, or ornithopters (flapping wing) systems for aerial flight.

Many of the challenges of mobile robot mechanical design lie in understanding how to move in challenging environments, including deformable terrain such as sand or mud, overcoming specific obstacles (like stairs), or climbing vertical surfaces. Tree-climbing robots have been developed, using wheels (Megalingam et al., 2021), arrays of small toes with sharp spines that engage with asperities in the climbing substrate, also known as microspines (Megalingam et al., 2021), “legs” that grasp the trunk (Lam and Xu, 2011), or trunk jamming mechanisms.<sup>3</sup> These platforms are much slower than human climbers and none have demonstrated the ability to reliably and repeatedly navigate trunks with branches. Other robots can deploy observation masts up to 12 m high using three interlocked steel tapes<sup>4</sup> or grow like a vine by everting thin plastic tubes using compress air (Haggerty et al., 2021). These could be deployed from the ground, from within the tree canopy, or from aerial platforms; however, they have many logistical issues that limit their successful deployment for research.

Aerial platforms have the advantage of being able to rapidly fly over an area to easily access the topmost branches of the tree canopy or for reconnaissance to identify and target sampling sites. In general, above-canopy flight is a simple task because of the presence of Global Navigation Satellite System (GNSS) signals, such as GPS, which allow the robot to accurately localize itself in the environment. However, below-canopy flight is much more difficult because the canopy effectively blocks all GNSS signals. Thus, aerial platforms that navigate below the canopy must be teleoperated or rely on sophisticated sensors such as vision or lidars coupled with advanced control and path planning algorithms for the robot to adequately localize itself. When operating above the canopy, suspended payloads could be transported by these platforms to collect samples or retrieve sensors near any structure in the canopy. UAVs have also been flown with nets to capture insects (Löcken et al., 2020) or various devices to capture spores (Crazzolaro et al., 2019).

Although direct contact with arboreal elements (leaves, twigs, fine vines) should generally be avoided, some UAV platforms are protected against intermittent contact (e.g., through physical guards or duct around propellers) or are even designed to take advantage of direct contact with their environment (e.g.,

using cages around the drone (Klaptocz et al., 2013; Kalantari and Spenko, 2014). This allows UAVs to fly within forests and inspect enclosed spaces, crevasses within glaciers, tunnels, or underground mines. Some aerial platforms can also land on high power electrical lines for in-contact inspection (Mirallès et al., 2018) or perch on surfaces/branches of various orientations for extended monitoring (Roderick et al., 2017; Hang et al., 2019; Mehanovic et al., 2019; Nguyen et al., 2019). Many new commercial UAVs now also have sensors to autonomously avoid obstacles when navigating around hiking trails, construction sites, or underground mines (e.g., Skydio, Emesent).

Mobile robots are commonly used to carry sensors to measure values of interest. The sensors (e.g., RGB cameras, range sensors such as lidars or radars, Infrared (IR) sensors, and hyperspectral cameras, among others) transported by the robot could be used to reconstruct the 3D environment through photogrammetry or point clouds (Scher et al., 2019). Many robots are also equipped with manipulator arms including end-effectors to interact with the environment (Zhang et al., 2020) through grasping or specialized samplers (e.g., branch cutter, aspirating devices, pumps, drills) to collect branches, flowers, bark, water, or insects. Robots could also be used to precisely install ropes or as a platform to deploy instrumented darts (Farinha et al., 2020) or other projectiles. Many industrial fields are investing heavily to advance robotics technology. These include aerial manipulation for structural inspection and maintenance, agricultural robotics, mining, manufacturing, fulfillment centers, medical robotics, autonomous driving, among others. Many of the technologies in these fields could be re-used to provide better access to arboreal ecosystems for research and management.

One of the main challenges with robotics is the required resources, expertise, cost and time needed to develop, use, and maintain these systems. To successfully develop tools that will be used in the field, coordinated efforts between scientists and engineers are required. Priority should be established by identifying the most pressing and common needs from scientists, but also the needs for which viable technological solutions can be developed by the engineering team. Equipment sharing should be favored, as well as concerted sampling efforts (i.e., collecting samples that can provide data for multiple studies). Technological solutions that can be used in multiple contexts can also be beneficial. For example, the creation of robotic augmentation to extend and improve the human ability to sample specific parts of the tree in structurally challenging regions of the canopy could be useful either for someone working from the ground or for someone who has climbed up the trunk of the tree. Likewise, devices developed to allow a hovering UAV to place a sensor precisely in the canopy could also be used by a person working from a canopy crane or walkway.

## FUTURE GOALS AND DIRECTIONS

Tree canopy research has grown substantially over the last three decades (Moffett and Lowman, 1995; Barker, 2015; Lowman, 2021), with an acceleration in innovative techniques and possibilities led by technological developments in sensors,

<sup>3</sup>[https://www.youtube.com/watch?v=2qKDixMgaqY&ab\\_channel=KAZ-corpLTD](https://www.youtube.com/watch?v=2qKDixMgaqY&ab_channel=KAZ-corpLTD)

<sup>4</sup><https://www.faulhaber.com/en/markets/factory-automation-robotics/zippermast/>

robotics, and UAVs. Here, we hope to facilitate this acceleration and focus innovation on the tools and technologies that could have the broadest impact and encompass the entire arboreal ecosystem. Experimental design, scientific questions, and management practices should not be determined by the methods and modes of accessing tree canopies. The community of scientists who study the biology of tree canopies originally had to overcome tremendous obstacles and recent developments are both a cause and a consequence of creative methods for accessing tree canopies (Barker and Sutton, 1997). Even today, most people working with trees state that their canopy access is limited and if they had effective and accurate equipment, they would routinely collect samples from the arboreal ecosystem.

This study represents a first step toward building a multidisciplinary community of academic scientists, tree professionals, and research engineers to address the limitations we face in accessing the arboreal ecosystem. The results provide important information from diverse perspectives about current abilities, limitations, and aspirations. Our virtual discussions, both synchronous and asynchronous, have created an effective framework for characterizing the methods and modes of accessing the canopy. To find common ground among these many interests and to maximize the impact for global efforts to study the arboreal ecosystem, we have identified four main priorities to advance these efforts:

- 1) broaden participation geographically and professionally;
- 2) identify the most common needs;
- 3) create teams of those who need access, e.g., biologists, with those who can help provide access, e.g., engineers and climbers, organized around common needs; and
- 4) establish a communication platform for sharing information.

Broadening participation, both geographically and professionally, will allow an effective interchange of advances, an efficient communication channel about different end user's values, and create opportunities for novel insights from under-represented perspectives. During the initial stages of our discussions, the responses to our survey were dominated by those working at institutions and universities in the United States and the United Kingdom. Subsequent discussions, during the virtual workshops and asynchronous collaborations on this manuscript, were more diverse, as demonstrated by the authors here. A more focused effort to include participants from tropical countries, is needed (Botanic Gardens Conservation International [BGCI], 2021). In some of these countries, the resources and infrastructure for research can be limited (e.g., Jarrín-V et al., 2021) or the value and emphasis of different types of research can be substantially different (Ciocca and Delgado, 2017).

Tree managers and tree care professionals, both municipal and private, work with trees every day and have a great deal of experience and motivation to access tree canopies. The value of trees in our built environment, both for human health and pleasure, has become increasingly apparent to the general public and city planners (Matsler et al., 2021). Combating pests, treating diseases, pruning, and assessing structural integrity of trees

would all be aided by easy, precise, and low-cost access to the tree canopy. Cheap and enjoyable means of obtaining arboreal samples could also allow community scientists to meaningfully participate and contribute to research related to community health, environmental justice, and important scientific questions about urban ecology and evolution (Langen et al., 2021). This connection between the public and the arboreal ecosystem can also be a powerful way to educate and inform students and tourists about its importance and value, even generating forest conservation and sustainable alternative incomes for indigenous people. To engage participants from these two different segments of global society, we will contact relevant societies and associations, international and national, like the International Society for Arboriculture, to learn how to make their members aware of our activities and objectives.

By identifying the common needs, we will form working groups that connect the scientists and professionals who need routine and efficient access with the engineers and roboticists with the appropriate expertise and interest to improve and invent the needed tools. Combining technical expertise from these two scientific fields may provide solutions through the application of existing technologies to the challenges faced in gaining canopy access (Cannon, 2012). By starting with the “lowest hanging fruit,” we can have the broadest impact and understand the functional requirements and engineering approaches that span several modes of access. The intersection of the means of access (e.g., canopy infrastructure, climbing, UAVs) with the needs of access (e.g., physical leaf sample, multispectral imagery, arthropod samples) will determine the best strategy for designing and improving these tools and how we might best incorporate robotic and engineering solutions.

Effective communication is important to any distributed and multidisciplinary effort. Given the rapid pace of innovation and change in global circumstances, we seek to establish an effective platform, built on existing social media networks and digital sharing technologies. This communication would not only coordinate activities and discussions within the network but would act as an information hub for technological advances, training opportunities, community events, and even expeditions. Informing the community about canopy samples being collected for one purpose can potentially have significant and simultaneous value for multiple research programs, especially for studies of sedentary plant associates (e.g., fungi, lichens, bacteria, mites, scale insects, whiteflies) and for samples collected in poorly known and remote tropical forests and other biodiversity hotspots. Researchers would benefit from standardized protocols for sample and data collection and distribution to allow for comparative studies across taxa and projects. The organization of workshops at large scientific and professional conferences, targeted events with municipalities and non-profits, and continued online virtual engagement will be an important part of growing the community and increasing inter-disciplinary and cross-agency collaborations and networking.

Finally, we recognize that expense and training will remain a barrier to entry for many people whose professional or personal

needs do not require regular tree canopy access. Efforts to remove these barriers, to maximize benefits and share the load as much as possible, will be sought. For example, the creation of regional hubs of expertise and equipment to facilitate the use or even provide service of canopy sampling tools or personnel to occasional or one-time users in the scientific and public communities, potentially even on a contract basis. This would help the community combine efforts and maximize benefit obtained from existing tools and expertise and innovate on new ones. Moreover, an awareness of the types of specimens sought by other researchers could potentially provide an easy solution for obtaining samples simultaneously for several purposes.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Illinois Institute of Technology. Written informed consent for participation was not required for this

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study in accordance with the national legislation and the institutional requirements.

## AUTHOR CONTRIBUTIONS

CC, CB, and MS conceived of the project and conducted the surveys. CC, CB, MS, and AD organized and led the workshops. CC and CB analyzed the data. CC, CB, DA, GA, MB, GC, and JR made substantial creative contributions to the manuscript. All authors contributed to the writing, editing, and revising of the manuscript.

## FUNDING

The research presented in this article was supported by the Center for Tree Science at The Morton Arboretum.

## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/ffgc.2021.712165/full#supplementary-material>

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- Conflict of Interest:** Some of the authors provide professional services, like tree climbing or sell UAV sample collection devices, that are discussed in the paper. The lead author and most of the other authors have no conflict of interest and have paid careful attention to any possible advocacy or promotion of a particular service caused by these select few potential conflicts.
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