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METHODS FOR HORIZONTAL MOVEMENT THROUGH FOREST CANOPIES

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ABSTRACT. Canopy access includes primarily vertical techniques for reaching the canopy from the ground, and canopy movement includes primarily horizontal techniques for moving through the canopy. Both directions of motion are necessary to fully explore and sample the forest canopy. Walkways, cranes, and rafts offer extensive canopy movement but involve substantial material, labor, forest impact, and freedom-to-research costs. In reviewing rope-based methods for canopy movement within forest canopies, the authors conclude that the advantages are (1) substantially lower costs, (2) lighter weight, (3) freedom for individual research teams to carry out replicated manipulative studies, and (4) greater availability of sample sites. Techniques developed by arborists provide within-crown movement, enabling transfers between trees less than 7 m apart. Special tools, such as the "mini-grapnel," extend traverse distances to 13 m. The authors describe a new technique based on a retrieval bolt (crossbow arrow) that allows crossing of gaps up to 40 m between trees without descending to the ground. They illustrate the application of these rope techniques in canopy research with a 200-m traverse through a 75-m-tall lowland rain forest, in which they establish a rope-based system to sample forest structure, microclimate, and arthropod distribution and abundance.

Key words: Borneo, canopy access, tree climbing, dipterocarp, tropical rain forest

INTRODUCTION

For decades, scientists have climbed trees to collect data on the biodiversity and ecology of forest canopies. Vertical canopy-access techniques for reaching the canopy from the ground have progressed to the point where reaching the top of very tall trees (>90 m) is routine. Vertical access techniques are suitable for sampling along boles or directly beneath large limbs; however, substantial biological activity in forest canopies occurs beyond trunks and other sturdy anchors. Biologically, the location of fresh leaves, flimsy twigs, and empty space may be the most significant yet least sampled site for wind, rain, and light interception; gas exchange, plant growth, and reproduction; pollination, herbivory, predation, animal movement, and other fundamental processes and interactions. To sample this biotically active zone adequately requires horizontal canopy movement techniques for moving within and between crowns and from tree to tree through the canopy, independent of the ground.

To date, canopy movements by research scientists have been largely limited to permanent and semi-permanent installations. Expensive, engineered solutions such as walkways (Bouricius et al. 2002), booms (Ashton 1995), cranes (Basset et al. 2003), and rafts (Hallé 1990) are typically shared facilities, constraining the types of samples and treatments imposed on canopy organisms. On the other hand, rope techniques for canopy movement, such as the "rope web" pioneered by Perry and Williams (1981), permit relatively inexpensive horizontal movement that allows for multiple samples at branch tips and even within the free space beyond. Skilled climbers can sample many trees per day, and ropes can be quickly removed after sampling is completed. While all techniques for canopy access and movement by humans can damage forest structure and organisms, rope-based methods are the least invasive. Nevertheless, careless climbing can injure a tree's cambium and epiphytes as well as endanger climbers' lives. Proper training therefore is necessary and best sought from experienced practitioners.

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Early contributions to the scientific literature concerning canopy access focused on single-rope techniques (SRT) as reviewed in Moffett and Lowman (1995) and Lowman and Wittman (1996), but many canopy scientists now employ a combination of rope techniques (e.g., Dial & Tobin 1994, Ellyson & Sillett 2003). Smith and Padgett (1998) review a variety of methods used in rock climbing and caving, including SRT. While SRT provides a safe, simple, and quick method of vertical access, horizontal movement within the canopy requires additional skills. The arboriculture trade has developed a range of techniques and equipment suitable for within-tree and limited between-tree movement, as arborists must often maneuver within large crowns for tree maintenance and care. Likewise, canopy scientists should replicate their observations within, between, and among crowns to increase sample sizes and inferential power.

In this paper, we first review arborist-style techniques with reference to their application to canopy movement. Such techniques are generally limited to travel within a single tree crown or between crowns less than 7 m apart. We then describe recent developments that allow movement between adjacent trees up to 13 m apart. Next, we present a new technique that allows canopy movement across gaps between trees up to 40 m wide. This method requires no assistants on the ground or in other crowns. In principal, a single, independent pair of climbers could begin in one crown and then move horizontally across an entire forest, sampling en route. We demonstrate the application of these techniques in canopy research by describing stages to establish a 200-m movement line through the canopy of a primary rain forest in Malaysia, where we sampled structure, microclimate, and arthropods throughout the canopy.

Methods

In general, moving horizontally through a forest canopy involves placing a rope from one limb across the top of a distant limb and retrieving the rope from under the distant limb. The rope can then be anchored, allowing the climber to move horizontally to the distant limb. The process of actually moving horizontally on ropes between limbs is straightforward, and several techniques can be used for a fixed rope (Smith & Padgett 1998). What is more problematic is how to (a) get the rope over the distant limb and (b) retrieve the rope from under the distant limb. To solve (b), there are three alternative methods depending upon the horizontal distance involved. The first rope-retrieval method is used primarily by arborists. The second two methods were used extensively in canopy research that we conducted during 2001–2002 in *Sequoia, Sequoiadendron,* and *Pseudotsuga* forests of western North America; *Eucalyptus* forests of southeast Australia; and a dipterocarp forest of Sabah, Malaysia.

Method 1: Pole Saw (up to 7 m)

Many rope-based methods well suited for canopy research originated in the arboriculture trade. Descriptions of rope techniques used by arborists can be found in Dial and Tobin (1994) and Jepson (2000); local arboriculture societies may provide instruction. In arborist-style climbing (also known as "double-rope technique"), one end of a rope is attached to the climber's harness, and the other end passes over a limb (preferably via a "cambium saver") and returns to the climber. A device (usually a friction hitch such as the prussic, taut-line, or Blake's hitch, but possibly a mechanical device) is attached to the rope to form a loop that can be shortened or lengthened, allowing the climber to move up or down the rope. With this method, the rope is always anchored within reach, and the climber can easily move and retrieve the rope while in the canopy.

Arborist-style climbing also can be used for canopy movement, for instance to sample throughout an individual crown or a cluster of nearby crowns. The climber, suspended on one limb, tosses a rope over a second limb in the same or adjacent crown with the goal of moving horizontally. To undertake a typical transfer, a climber may toss the other end of a "split-tailed lanyard" (available through Sherrill Arborist Supply, Greensboro, North Carolina, USA, www.sherrillinc.com) over a second limb located up to 7 m away. The split-tailed lanyards we use are 20-m-long ropes with spliced eyes on each end. The eyes are used to attach the lanyard end to the climber's harness via steel carabiners. Near each end of the lanyard is a second, shorter (1.5 m) piece of rope, the "split-tail," attached to the lanyard with a friction knot (preferably the Blake's hitch) and to the climber's harness with an aluminum carabiner. Jepson (2000) describes the single end split-tail technique. The purpose of the two tails is to allow the climber to use both ends of the lanyard simultaneously for traversing between limbs. Separate ropes, each with a single split-tail, also can be used. In the double end split-tailed lanyard method, one lanyard end is under tension supporting the climber, and the other loose end is tossed over the distant limb in anticipation of supporting the climber. Sometimes, as in traversing, both ends take the climber's weight simultaneously.

The tensioned end of the lanyard is anchored to and supporting the climber from the original limb via a split-tail loop. To place the loose end of the lanyard over a distant limb, the climber carefully makes tidy coils (20–30 cm in diameter) of the lanyard in one hand and tosses them over the distant limb. The coils provide both the weight to reach the distant limb and the slack to hang beneath the limb for retrieval. If needed, extra weight can be added by tying a "throwing knot" (Jepson 2000) or by attaching a steel carabiner to the eye of the lanyard prior to throwing. The lanyard tail with its aluminum carabiner is never thrown and remains close to the climber. If additional rope is needed beneath the limb to facilitate retrieval, the climber throws slack over the limb (similar to the way a fly fisherman casts extra line), by sending coils overhand down the rope.

Arborists typically climb trees for pruning purposes and often carry pole saws with extendable handles 1–7 m long and special hooks for grabbing rope. These can be used to retrieve the rope beneath the distant limb. After retrieval, the loose end of the lanyard is clipped to the climber's harness with its steel carabiner, and the slack is pulled through the tension knot of the tail, which is now clipped to the climber's harness, forming a second split-tail rope loop around the distant limb. Now the climber simply lowers off the original limb with the first split-tail and uses the second split-tail to pull across to the distant limb. Once the distant limb is reached, the steel carabiner end of the lanyard leading to the original limb is unclipped from the harness, and the slack end is retrieved and ready for another transfer. In essence, movement between any limbs strong enough to support the climber's weight is possible within a distance reachable by the saw.

Method 2: Mini-Grapnel (up to 13 m)

A more efficient method to move laterally within wide crowns is desirable, because pole saws are cumbersome and horizontal distances greater than 7 m are regularly encountered in large trees such as tall conifers, dipterocarps, and strangler figs. Climbers working in the tall conifers of western North America developed four-pronged, miniature grapnel hooks (hereafter "mini-grapnels") to facilitate lateral movement. A "throw bag" (a 280–420 g weighted bag commonly used for access by arborists) tied to high-visibility cord stacked in a "line mug" (a nylon bag approximately 0.75 L in volume) can be thrown over more distant limbs than can the heavier rope lanyard. The mini-grapnel (New Tribe, Inc. Grants Pass, OR, USA, newtribe@cdsnet.net) can be used to snag rope or cord up to 13 m away. We attach the mini-grapnel to fly-fishing line loaded on automatic rewind reels mounted to our climbing harnesses with metal braces. The spring-loaded reels minimize tangling and permit quick retrieval and storage of the mini-grapnel and line. The best reel we have found is a device called the "Miracle Silent Automatic" (no. 1697), which was manufactured by Kalamazoo Tackle Company in the 1950s. These can occasionally be found in antique stores or on eBay (search for "automatic fly reel"). An adequate alternative, the Orenomatic® automatic fly reel, is still manufactured (South Bend Sporting Goods, Northbrook, IL, USA). An automatic rewind dog leash may serve the same purpose.

Using the mini-grapnel requires both good hand-eye coordination and patience, but it offers several advantages over throwing a line to the ground over the distant limb, descending, anchoring, and re-ascending. First, it is faster, especially in tall trees. Second, it reduces the substantial impact climbers can have on ground vegetation; and third, the technique requires significantly less rope to move across a given horizontal space since the distance to the ground plays no role in the amount of rope needed. The idea is to toss or swing the grapnel at a target line, pulling back at just the right instant to grab the target line in the grapnel's prongs. In the case of a throw bag tossed over a distant limb to make a transfer, the cord is snagged with the mini-grapnel and then pulled over to the climber. Once the cord is in hand, the throw bag is untied, the mini-grapnel and line are stowed, and the cord is tied to a climbing rope. The cord is pulled hand-over-hand to bring the climbing rope over the distant limb and back to the climber. The climber now has a rope loop containing the distant limb, and the transfer can be made using standard techniques (e.g., Dial & Tobin 1994, Smith & Padgett 1998, Jepson 2000).

In the course of moving horizontally through forest canopies during 2001–2002, we made 10 of 32 tree-to-tree transfers using the mini-grapnel. The mean horizontal distance of these mini-grapnel transfers was 8.3 m. The maximum was 13 m in a very open *Eucalyptus regnans* forest in Victoria, Australia. Mini-grapnels also are useful for rigging sampling lines or anytime a line is out of reach but within about 10 m of the suspended researcher.

Method 3: Retrieval Bolt (up to 40 m)

Since emergent trees in many forests are spaced more widely than the reach of a mini-grapnel transfer, we developed a method for

FIGURE 1. A retrieval bolt being fired at a throw bag line in an adjacent tree. Photograph courtesy of Bill Hatcher Photography.

transferring between trees standing farther apart. The method requires a 150-lb pull crossbow with an affixed open-face spinning reel and a special crossbow arrow that we call the "retrieval bolt" (FIGURE 1). The retrieval bolt has a 50-cm long, 8-mm diameter fiberglass shaft with a removable "retrieval head" attached to the distal end. A 2-mm hole is drilled in the tail end of the bolt shaft to attach a fishing line (e.g., 20-lb test Fireline® filament) that is spooled onto the reel mounted to the crossbow. The specialized retrieval head of the bolt is designed to snag the cord tied to the throw bag hanging beneath the distant limb. The snagging is accomplished using the re-curved tines and back barbs on the retrieval bolt's head.

The retrieval bolt head itself is made from four individual 22 cm × 2 mm metal rods welded in parallel around a 1-cm diameter metal nut 3 cm from the ends of the rods. Before first use, the long end of each rod is formed into recurved tines, and the short ends are bent slightly out from the shaft to form back barbs. We curve the tines at an angle of 45° away from the shaft and then bend each one back sharply so that the four tips barely touch in the center 5 cm above the nut. Before bending the tines, we bolt the nut onto an aluminum mount that is glued onto the fiberglass shaft with "ferrule cement" (available at sporting goods stores that deal in fishing equipment). The mount is assembled by cutting appropriate diameter, hollow, aluminum arrow stock into 5-cm pieces and cementing the appropriate diameter threaded plugs (a bow hunting product typically used at the end of aluminum arrows to affix arrow heads) into one end. The retrieval bolt head is screwed onto the mount on the shaft immediately prior to use. Unused retrieval bolt heads are stored in compact clusters inside belt pouches.

Once the throw bag is tossed over a sturdy limb in an adjacent tree (FIGURE 2A), and the retrieval bolt is assembled with the fishing line tied to its end, the climber loads the bolt onto the cocked crossbow, aims at the high-visibility cord through a clear "window" in the foliage below the distant limb (but above any other limbs), and fires (FIGURE 2B). Sometimes we snag the cord with the first shot of a retrieval bolt. Other times, the line breaks, we lose the bolt, and use another. Most bolts snag in foliage. About 30–100% of these bolts are not recovered, until we arrive at the distant limb; others are lost below. In general, we require 1–12 attempts to snag the cord, although one 27-m gap required 19 attempts with the retrieval bolt. Retrieval bolt losses are the primary drawback to the technique, but retrieved bolts are still functional and can be used again. Damage to a bolt consists of the progressive weakening and eventual loss of tines. After a retrieval bolt snags a line, its tines must possess sufficient stiffness to hold the cord for retrieval by the climber. As the tines break, bolts may be re-used effectively down to two remaining tines. Even if all four tines are lost, the back barbs on each bolt still allow them to be used as long-range grapnel hooks.

The retrieval of the bolt with its snagged cord is easiest with two or three people (FIGURE 2C). Immediately after snagging the cord, the shooter hands the crossbow to another climber who can reel in the fishing line as the shooter pulls by hand. The shooter must be careful to pull without breaking the fishing line or losing the cord. A third climber can assist the process by gently tugging or feeding the cord out of the line mug, as the throw bag end of the cord is pulled by the shooter. The process is intended to retrieve the cord while preventing tangles. Tangles rarely allow cord retrieval and in some cases require cutting the cord.

In 2001–2002, we made 22 of 32 tree-to-tree transfers using the retrieval bolt. The mean horizontal distance of these retrieval bolt transfers was 20.1 m. The maximum was 40 m in a *Sequoiadendron giganteum* forest in California, USA. The technique may be applied to sampling the branch tips and empty space around a focal crown by establishing a radial array of lines from the focal tree to nearby ones.

Traverse Techniques

Once the cord is retrieved, a 9–12 mm static kernmantle rope is tied to the end and pulled by the climbers across the gap, around the distant limb, and back to their position (FIGURE 2D). While the rope must be at least somewhat longer than twice the gap length, if it is somewhat more than thrice the gap length, it can often be rigged more cleanly. The rope will be in a large loop and almost invariably will include some foliage inside the loop. The physics of "high-lines" and catenaries (see, for instance, Graydon & Hanson 1997) impose non-linear, accelerating forces on the line and its anchors, the closer the traverse line is to the horizontal. While the breaking strengths of ropes and other climbing gear are well known and even certified by international organizations, it is impossible to accurately gauge the strengths of limbs or trunks used to anchor traverse ropes, especially since the distant limb has not been inspected. In particular, a limb or trunk that easily can support a climber's downward pulling body weight on rappel may suffer catastrophic failure if pulled horizontally by a force five times or more than the climber's

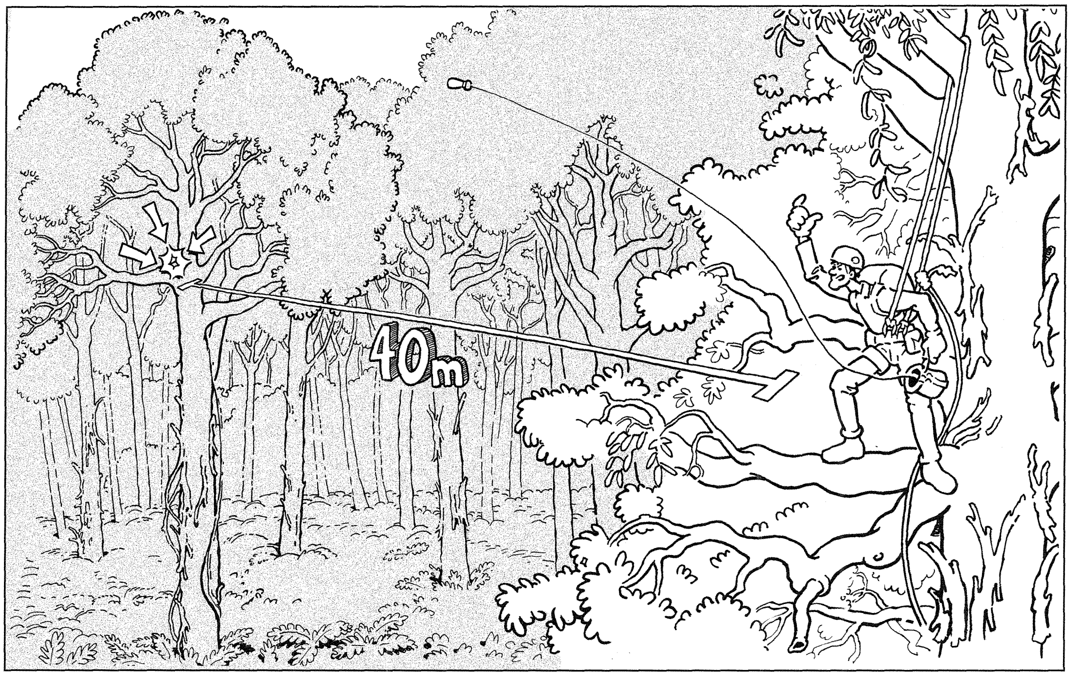

FIGURE 2. Traversing between trees using the retrieval bolt method proceeds in eight stages labeled here as A–H (see text for descriptions). Drawings by Bryan Kotwica. FIGURE 2A. Making the throw bag shot.

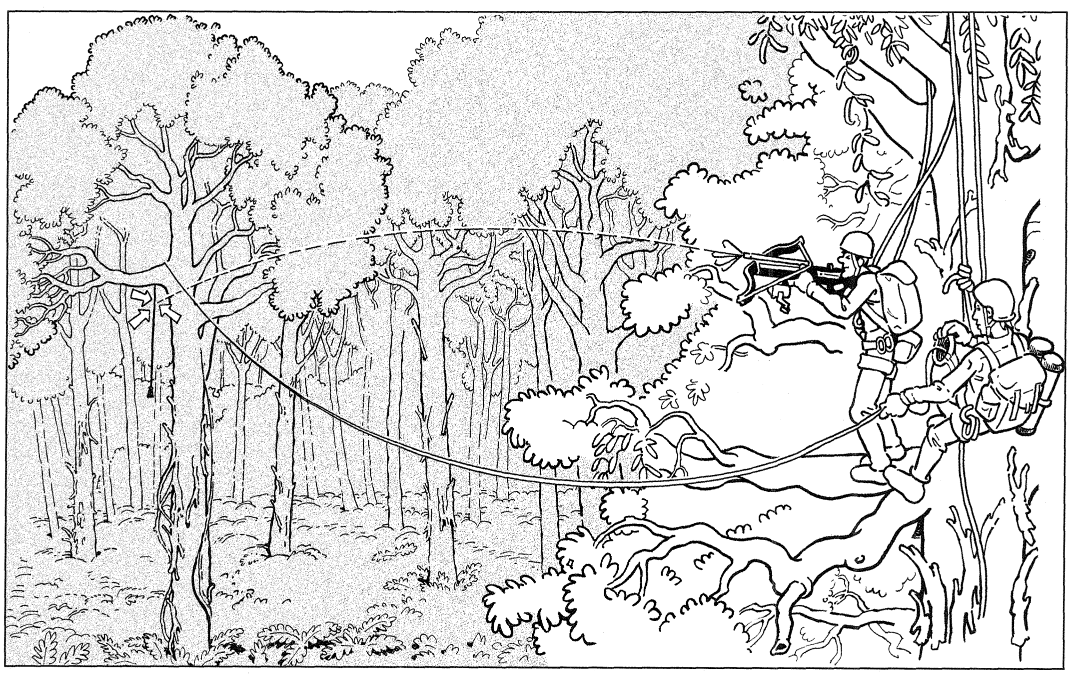

FIGURE 2B. (Continued) Shooting the magic missile.

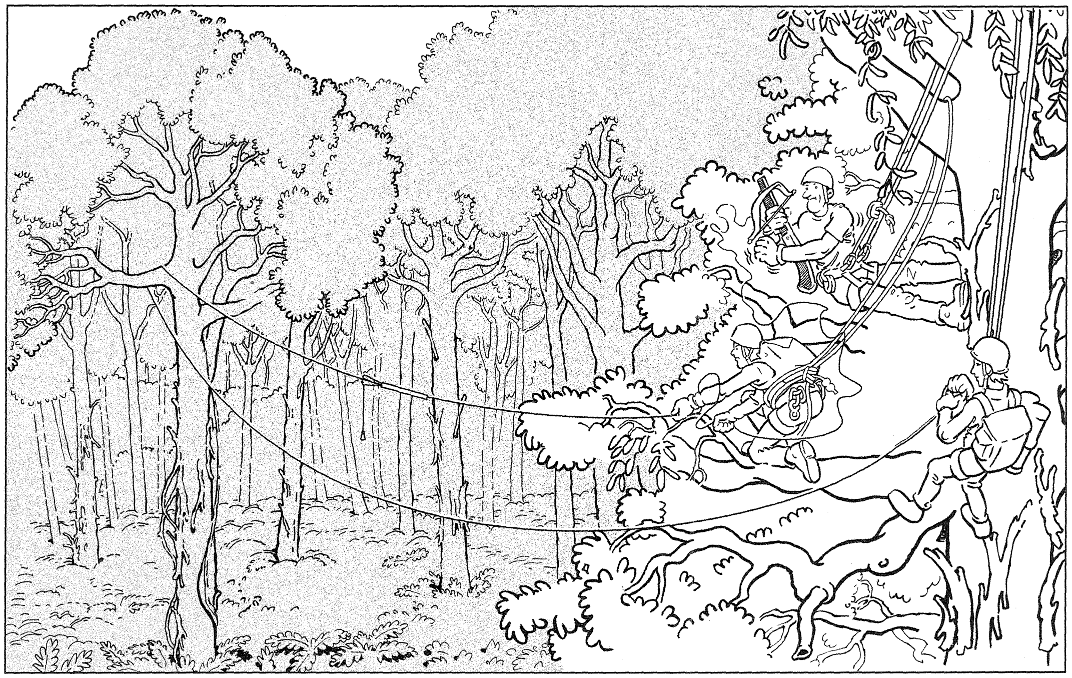

FIGURE 2C. (Continued) Retrieving the throw bag line.

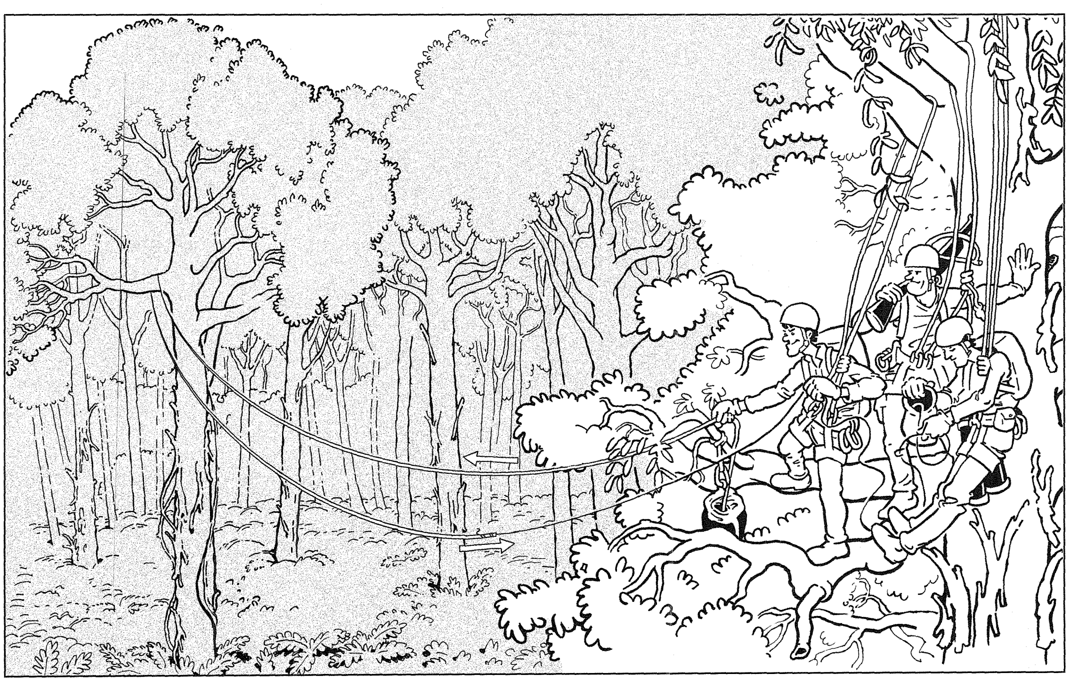

FIGURE 2D. (Continued) Pulling the traverse line.

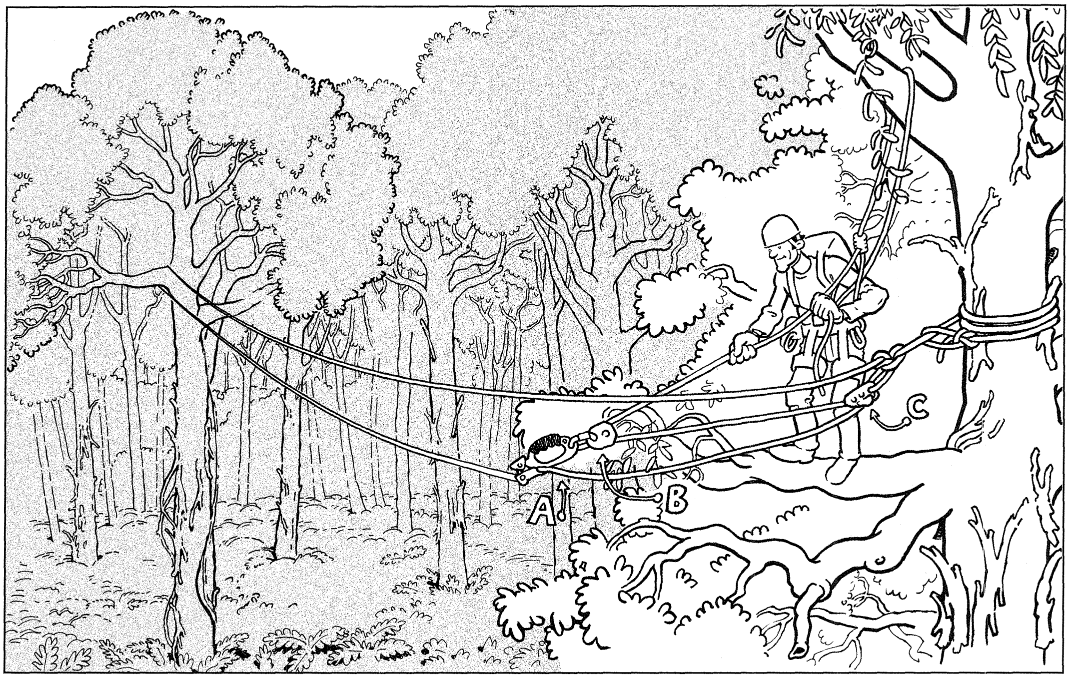

FIGURE 2E. (Continued) Tightening the traverse line. ***A*** = ascender. ***B*** = pulley. ***C*** = Petzl® Gri-gri.

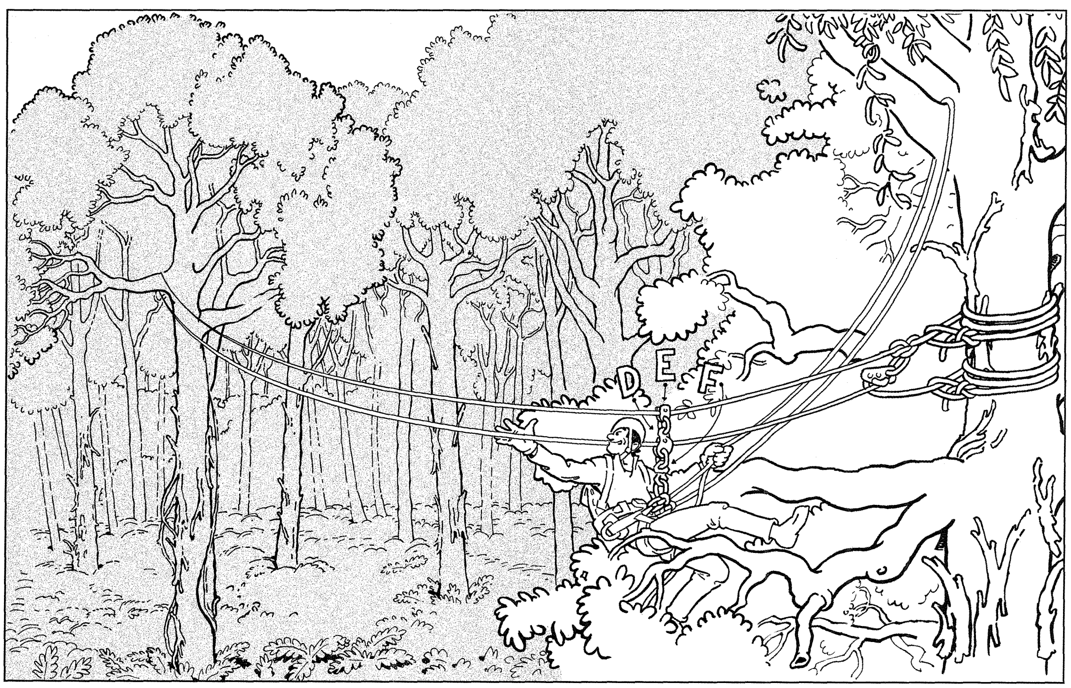

FIGURE 2F. (Continued) Making the traverse. ***D*** = Petzl® Pro-Traxion. ***E*** = pulley. ***F*** = Petzl® Swivel.

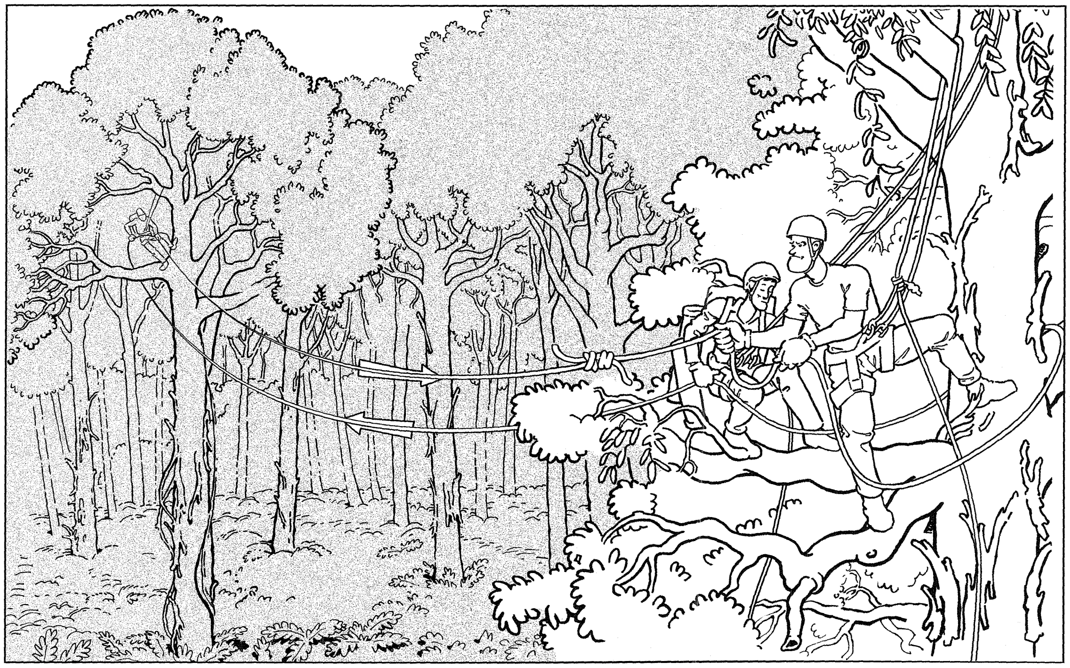

FIGURE 2G. (Continued) Switching the anchor tree.

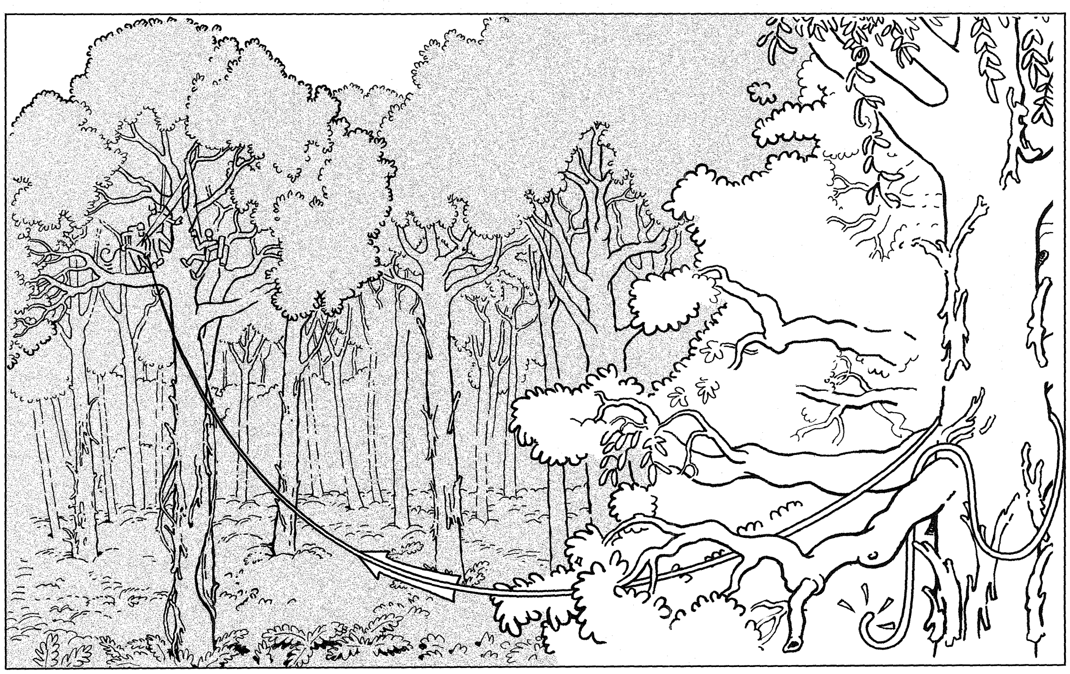

FIGURE 2H. (Continued) Retrieving the traverse line.

weight, as on a tight traverse. The maximum force on the anchors occurs when the climber is at the midpoint of the traverse. If A is the angle of the rope at midpoint with a climber of weight W, then the force T exerted on each anchor is given by $T = 0.5\ W \sec(A/2)$. Note that as A approaches 0 degrees, T approaches 0.5 W; however, as A approaches 180 degrees (a perfectly level rope), T approaches infinity, because of the behavior of $\sec(A/2)$. This is more than a theoretical construct: limb failure can be lethal. For that reason we leave a bit of slack in our traverse rope; the loss of a vertical meter is an acceptable trade-off for safety.

We usually take one end of the rope, wrap it around the trunk of the tree we are leaving, and then secure it with a self-cinching, running bowline (Jepson 2000). Then we use a Z-pulley system (Smith & Padgett 1998) to tighten and anchor the rope (FIGURE 2E). This system is well suited to rigging traverses to sample the space between branches, trees, and branch tips. The Z system is so-called, because the rope passes two bends with pulleys, as in the letter "z." Our Z system uses a bight of the traverse rope tied as an anchor around the trunk. We clip a locking carabiner to the anchor. To this, we set a Petzl® "Gri-gri," which is normally used as a belay or rappel device; here it allows us to tension the rope in the place of a pulley. The Gri-gri is placed so that the "up" direction on the device points toward the far end of the traverse. The rope running out of the "down" side of the device is then placed around a pulley attached to an ascender located between the Gri-gri and the far end of the traverse but within easy reach. The rope exiting the pulley is pulled, tensioning the system, with the Gri-gri holding the tension. When the rope is sufficiently tightened, one climber leads out on the traverse by clipping a pulley to the rope and lowering onto the traverse line using the split-tailed lanyard (FIGURE 2F). Only the lower rope is used by the first climber, unless it is clear that no intervening limbs or branches are inside the loop, in which case both lines are used simultaneously. Once fully lowered on the lanyard (about 10 m), the lead climber must release the lanyard and commit to the traverse rope. From this point until reaching the distant limb and securing to an independent limb, the climber is at tragic risk from limb failure.

When the lead climber has safely reached the distant limb and secured to another limb, the other climbers loosen the traverse rope with the Gri-gri and untie the anchor. The two ends of the rope are tied together behind the trunk, and the lead climber then pulls on one side of the loop to haul the knotted end across the gap (FIGURE 2G). During this process, it is possible to rig the traverse so that no branches intervene in the loop. This rigging requires a rope at least three times the gap length, and the lead climber must send the re-routed end back to the climbers on the other side of the obstruction and back again. When the rope has been re-routed, the lead climber installs the anchor and Z-pulley system on the new trunk, and tightens the traverse rope. This process is best carried out by climbers who know rope-craft well and are in contact via radio. Now the other climbers can follow, preferably by using two pulleys, one on each side of the rope loop (top and bottom) without intervening foliage. Using two pulleys minimizes sag in the rope, allows for higher, quicker traversing, and is preferable to overtightening the traverse line. After all climbers make the traverse, the traverse rope is loosened and pulled out of the original tree (FIGURE 2H). The process can be repeated as long as appropriate limbs are available and within reach of the throw bag toss.

During five days in April 2002, we traversed through the crowns of 11 trees traveling a total of 200 m horizontally across a lowland rain forest astride the Tambaling Stream of Danum Valley, Sabah, Malaysia (TABLE 1). To choose an appropriate stand for the traverse, we considered three criteria: (1) primary forest with tall, healthy specimens of Dipterocarpaceae and *Koompassia,* (2) relatively level ground, avoiding steep hillsides and ridges, and (3) within one-hour of the Danum Valley Field Centre. The stand we selected spanned a creek with tall trees on either side. To portray our traverse (FIGURES 3, 4), we measured the main trunk and crown of each tree and mapped each tree's base on a three-dimensional coordinate system relative to the creek. Two types of crown measurements were made: structure and spread. To document crown structure, we stretched a fiberglass tape from the treetop to average ground level and recorded heights of major branches, limbs, and forks, then photographed the crown of each tree from adjacent trees. These measures were used to construct a proportioned profile diagram of the canopy where we moved horizontally (FIGURE 3). The crown spread of each tree was calculated as twice its average crown radius. Crown radii were measured by shooting horizontal distances with an Impulse® laser rangefinder (Laser Technology Inc., Englewood, CO, USA; www.lasertech.com/productline/impulse.htm) from the crown edge to the main trunk along eight azimuths (N, NE, E, SE, S, SW, W, NW). These crown distances were used to construct an aerial view of the movement path showing crown projections of each tree (FIGURE 4).

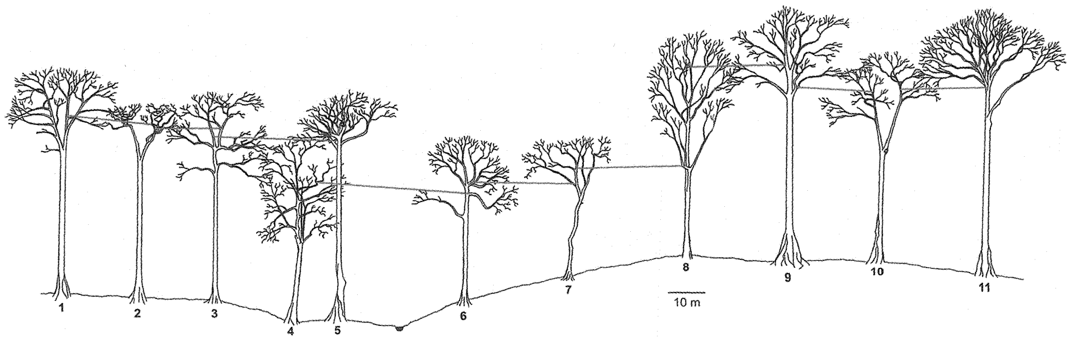

FIGURE 3. Profile diagram of the 11 trees traversed over 200 m of canopy movement in Danum Valley, Sabah, Malaysia. See TABLE 1 for tree identities and dimensions. Horizontal lines indicate rope traverses between trees with techniques used to move between trees (see TABLE 2). All tree dimensions as well as horizontal distances of the four longest traverses (i.e., Trees #5–6, #6–7, #7–8, #10–11) are proportional to the scale bar, but horizontal distances of the shortest six traverses are slightly expanded to better illustrate tree structure. Positions of ground level and the stream between Trees #5 and #6 also are indicated.

We gained initial access to the forest canopy by using a compound bow to shoot a rubber-tipped fiberglass arrow (trailing fishing line) over limbs above 60 m in the crown of Tree 1. The filament was used to haul a 3-mm buntline cord to position a 200-m 11mm rope. After anchoring one end of the rope at ground level, we climbed into the tree using SRT. TABLE 2 describes the techniques used for transferring into each successive tree.

DISCUSSION

After making the traverse shown in the figures and tables, we established a higher, 2-segment, 130-m traverse line. From this traverse line, one of us established a series of seven vertical transects from the ground to the traverse line at 20-m horizontal intervals forming a canopy-sampling matrix 130 m long and 55–65 m high. Along each 55–65 m vertical transect, samples

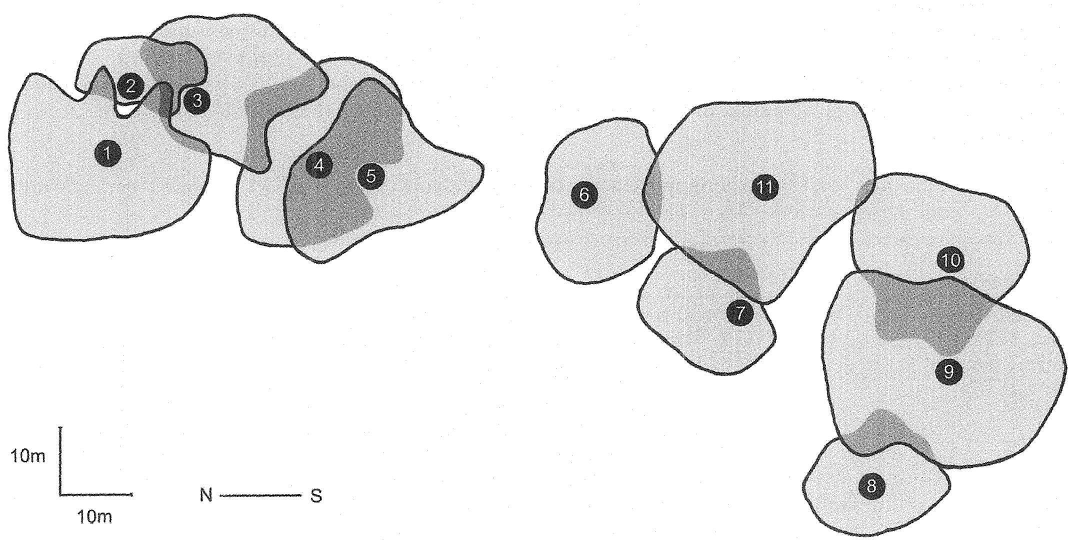

FIGURE 4. Aerial view of crown projections of 11 trees shown in FIGURE 3. Position of each tree's main trunk beneath the crown is indicated by a black, numbered circle. See TABLE 1 for tree identities and dimensions. See TABLE 2 for movement techniques. Imbrications of crowns are indicated by shading. All distances are proportional to the scale bars.

TABLE 1. Identities and dimensions of transfer trees along canopy traverse shown in FIGURES 3 and 4.

Key	Species	Family	Height (m)	Basal diameter (m)	Diameter above buttress (m)	Buttress height (m)	Crown spread (m)
1	*Shorea leprosula*	Dipterocarpaceae	66.0	3.4	1.5	5.2	28.4
2	*Parashorea malaanonan*	Dipterocarpaceae	55.8	3.1	1.3	9.1	14.0
3	*S. parvifolia*	Dipterocarpaceae	59.2	1.9	0.9	4.3	20.9
4	*Pentaspodon motleyi*	Anacardiaceae	52.6	3.8	1.1	6.0	26.8
5	*S. johorensis*	Dipterocarpaceae	63.0	4.0	2.0	6.2	22.8
6	*S. johorensis*	Dipterocarpaceae	48.0	2.4	1.0	2.9	20.4
7	*Dialium indum*	Fabaceae	40.8	1.4	0.7	2.5	17.4
8	*Azadirachta excelsa*	Meliaceae	61.9	1.6	1.1	2.1	19.0
9	*Parashorea malaanonan*	Dipterocarpaceae	72.8	9.1	1.5	10.9	32.2
10	*P. tomentella*	Dipterocarpaceae	59.2	4.1	1.3	8.8	25.4
11	*Koompassia excelsa*	Fabaceae	75.0	3.9	1.3	9.4	29.7

of structure were taken at 2-m vertical intervals (Dial et al. 2004); samples of light, relative humidity, and temperature at 3-m vertical intervals; and samples of canopy arthropods at 5-m vertical intervals. The sampling matrix could just as well have been a radial, crown-centered one, if the questions had been tree-specific rather than stand-specific.

Using a crown-centered approach, the movement techniques described above can be applied to establish a radial sampling system originating from each crown's trunk and into the space between crowns. Three to twelve such radiating transects can be established using mini-grapnels and retrieval bolts together with the split-tailed lanyard system. Radiating transects like these allow for intensive horizontal sampling from trunk to branch tips and beyond. This approach is well suited, if single tree species studies are the focus, as, for instance, in determining the host specificity of canopy arthropods; the distribution and physiology of leaves, reproductive structures, fruits, and epiphytes across branch ages or diameters; intra- to inter-crown microclimatic gradients; and horizontal heterogeneity in foliage density, crown architecture, and canopy structure. Indeed, we sense that canopy science in general is plagued by poor horizontal sampling effort. This occurs for two main reasons. First, rope methods, which are inexpensive and less subject to regulation, are poorly developed. Second, engineered methods, although well developed and secure, are localized and limiting either because of funding or policy. We offer the techniques described in this paper to empower canopy scientists to more fully explore the canopy environment with replication and experimentation.

The described techniques are not without drawbacks. The techniques demand skills in rope handling and arborist-style tree climbing, as well as some specialized equipment. As we

TABLE 2. Techniques used for canopy movement shown in FIGURES 3 and 4. SRT = single rope technique; STL = split-tailed lanyard; FTL = fixed double 11-mm traverse line.

Transfer	Distance (m)	Technique
Ground–Tree 1	60	Compound bow for initial access from ground; SRT
Tree 1–Tree 2	10	STL to Tree 1 outer limbs; STL and mini-grapnel to Tree 2
Tree 2–Tree 3	8	STL to Tree 2 outer limbs; throw bag and mini-grapnel to Tree 3; lanyard as SRT
Tree 3–Tree 5	28	STL to Tree 3 outer limbs; throw bag and retrieval bolt to Tree 5; FTL
Tree 5–Tree 6	32	STL upward and outward in Tree 5 outer limbs; throw bag and retrieval bolt to Tree 6; Tree 4 accessed from Tree 5 using STL; FTL from Tree 4 to Tree 6 because of epiphyte load on Tree 5
Tree 6–Tree 7	28	STL upward and outward in Tree 6; throw bag and retrieval bolt to Tree 7; FTL
Tree 7–Tree 8	32	STL upward and outward in Tree 7 to pass liana tangle; throw bag and retrieval bolt to Tree 8; FTL
Tree 8–Tree 9	20	STL upward in Tree 8; throw bag and retrieval bolt to Tree 9; FTL
Tree 9–Tree 10	16	STL outward in Tree 9; STL and mini-grapnel to Tree 10; STL and limb walking (Jepson 2000) inward into Tree 10
Tree 10–Tree 11	28	Throw bag positioned from Tree 9; retrieval bolt used from Tree 10; FTL

currently use arm strength alone to place the throw bag, horizontal distance and accuracy might well be improved by using a large "slingshot" apparatus to hurl the throw bag. The canopy movement methods described here also have a certain degree of danger, similar to initial access in SRT in that the distant limb is untested. During canopy access, clear views of the high anchor point are often unobtainable from the ground, and there is considerable risk of limb failure or falling debris during the initial SRT ascent. In contrast, such dangers are lessened during canopy movement, because the distant limb can be seen clearly (especially with the aid of binoculars), and climbers on traverse are not in the path of falling debris. Unlike SRT, however, the climber on traverse may be very high off the ground on an untested limb. Limb failure could well be tragic, and the nearly hyperbolic increase in forces, as the traverse line approaches horizontal, should restrain an enthusiasm shown very taut high-lines. Sound arboricultural judgment, which is based on considerations of tree health and architecture, and an understanding of the physics involved can minimize but not eliminate this risk.

Taken individually or collectively, movement methods can greatly extend a researcher's ability to sample forest canopies. The mini-grapnel, combined with the split-tailed lanyard, provides efficient access to the outer crowns of large trees and complements SRT access. The retrieval bolt provides unique opportunities to reach the crown periphery and spaces beyond. Even crowns otherwise inaccessible because of animals, rot, or other safety issues, such as standing dead trees, can be accessed. The methods we describe, while substitutable by tossing ropes over distant limbs for anchoring on the ground, require far less rope and are more time efficient, because ground support is not needed and climbers can remain in the canopy. We offer them to assist scientists who need to access nearby trees without recourse to more expensive engineered solutions (e.g., cranes, rafts, walkways, zip-lines) or even ground-based assistance.

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