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Canopy Access Techniques

Mark W. Moffett and Margaret D. Lowman

> *To know the forest, we must study it in all aspects, as birds*
> *soaring above its roof, as earth-bound bipeds creeping*
> *slowly over its roots.*
> —*Alexander F. Skutch, "A Naturalist in Costa Rica" (1971)*

I. Introduction

In this chapter, we have intentionally departed from the rigorous scientific presentation of the other authors. Our chapter does not offer hypotheses or results; rather, it is a *story* of the development of one of the most exciting and innovative frontiers of ecology. The "heroes" of this tale are the scientists whose writing follows ours, and their pioneering studies are setting the stage for the young researchers and students who may become stimulated by the discoveries reported here. We have, however, highlighted three pioneering techniques in the development of canopy biology (see Boxes).

We emphasize an important underlying message with our review of canopy methods: *SAFETY.* To all who become inspired to attempt canopy research, and particularly those who have not previously worked with experienced arborists or canopy biologists, please be cautious and use all possible safety precautions. Though our descriptions are intended to entice, the concepts of canopy access require serious attention to safety measures.

In contemplating the tangled web of species interactions in forest canopies, scientists have relied so far on sparse information. As this volume

shows, canopy biologists must dangle precariously for hours to find out such basic data as where innocuous ants horde epiphyte seeds; chart the complex pathways of lianas to sunny spots where they flower; trace the passage of nitrogen from tissue to tissue through floral arcades; and loiter for weeks in aerial blinds to observe the fruit preferences of enigmatic birds. Concentrated endeavors of this kind are cornerstones to an intimate understanding of treetop ecology (Lowman and Moffett, 1993). Nonetheless, many canopy biologists still invest as much time and effort to get into the trees as to collect data from them. This chapter reviews the practical side of the researcher's canopy experiences.

Although canopy access technologies have expanded over the last 15 years or so, many of the methods can be traced back to antecedents from decades earlier (reviews in Mitchell, 1982; Moffett, 1992). Entire volumes that report climbing techniques in the field have been written by Hingston (1932), Mitchell (1981), Perry (1986), Moffett (1993b), and Lowman (1995). Of the modern methods reviewed here, some require shrewd financial lobbying, whereas others can be managed on a shoestring budget; some are cumbersome and reach a limited area, whereas others allow scientist to touch the tips of lofty branches with the grace of an acrobat. Most are currently in use somewhere in the tropics, and every one has merit unde the right circumstances.

Our review emphasizes tropical rain forest situations mainly because th widest variety of techniques has been attempted in this tall, most architecturally complex forest type. The chapter starts by addressing stratagems fo gathering canopy data from the ground. Thereafter, our coverage focuse on techniques created to actually transport people into the treetops.

II. Techniques of Canopy Access

A. Ground-Based Methods of Access

It is by no means necessary to climb into the canopy to complete a cano study. For collecting many kinds of data, climbing would be a waste of tim Ground-based methods are notably useful in studying species that are ther extremely mobile or too sensitive to disturbance to be monitored fro within the canopy, in gathering museum samples (such as plant specime or bird skins), or when the sampling protocol is so demanding that it impractical to climb so often.

Nearly every naturalist has taken advantage of a ridgetop to view the ca opy at its own level, close at hand, even if only to ponder the magnificen of the treetops. Some biologists actually get better information from a go ground-based vantage point. For example, primates can be tracked with t greatest ease from the ground, binoculars or telephoto lens in hand (see Chapter 10). Day-Glo colors painted on reptiles permit the location and identification of cryptic species in the trees (Robert Henderson, personal communication). Concealed vertebrates can be located and tracked by radiotelemetry (e.g., Montgomery *et al.*, 1973). Fish-eye photographs of light flecks in the canopy can be analyzed by computer to determine the light regimes at specific understory positions (Becker *et al.*, 1988). Canopy data can be gathered photographically from above the trees with the aid of balloons, ultralight aircraft, or—from still higher up—planes and satellites (O'Neill, 1993). With the aid of binoculars, most canopy trees can be identified quickly by the experienced eye (e.g., Robin Foster, personal communication) (Fig. 1).

In collecting canopy plant specimens there are several alternatives to climbing trees (see also Chapter 23). E. J. H. Corner (1992) reported that

Figure 1 Robin Foster using binoculars to identify canopy plants.

domesticated monkeys were trained in Malaysia in the 1930s to retrieve botanical samples from the canopy:

> By means of the coconut or pig-tailed monkey (*Macaca nemestrina*) . . . I obtained, at last, a fair measure of the forest without destruction of the trees. Hitherto, baffled by the height of trees, climbers and epiphytes, I had been obliged to content myself with forest that was being felled. That was hard, hot, and commonly unsuccessful work, for the plants were often neither in flower or fruit. I grew to detest climbing over a jumble of fragments in the endeavor to piece them together, while streaming with sweat, harassed by the glare, and often assailed by irate bees and wasps. . . . [Using monkeys] I developed a rubber neck that I could lay back on my shoulders for half-an-hour at a stretch, while gazing upwards and shouting commands to the treetops.

Similar plant (or animal) sampling can be accomplished from the ground with a slingshot, rifle, or (for low branches) a pole pruner (Fig. 2). Fogging trees with insecticide is another "knock down" approach to sampling, but applied only to invertebrates (Erwin, 1989; Kitching *et al.*, 1993; and Chap-

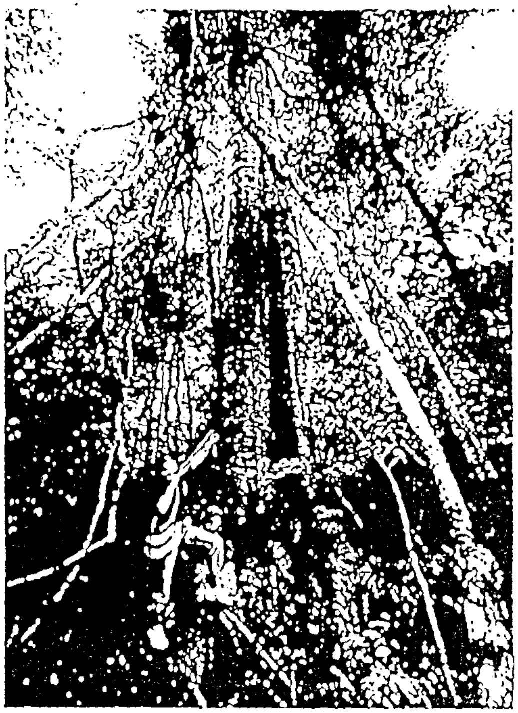

Figure 2 Darlyne Murawski using a slingshot to knock down fruits of a cuipo tree in Panan for isozyme analysis.

Figure 3 Terry Erwin fogging for arthropods in a Peruvian tree crown as part of his biodiversity studies.

ter 5) (Fig. 3). Without climbing a tree, D. H. Murphy (personal communication) collects airborne insects with sticky traps raised to the canopy by tethered helium balloons. The normal "rain" of canopy organisms and debris can also be assessed with litter traps (e.g., Lowman, 1988).

A widely applicable ground-based technique involves hoisting an apparatus into the canopy with a pulley system, then lowering it as required to check an experiment. An initial climb into the canopy may be required to set up a pulley, or researchers may elect to shoot a line over a branch from the ground and use that line to pull up and support a second haul line on a pulley. This has been done with mist nets (Munn, 1991), light traps (Wolda, 1992; Sutton, 1979), butterfly bait traps (DeVries, 1988), mammal traps (Malcolm, 1991; Deedra McClearn, personal communication), branches harboring epiphytes (Cristian Samper, personal communication), trays that hold sprouting fig seeds (Timothy Laman, personal communication), and numerous other experiments.

Table I Methods for Canopy Access and Assessment of Their Use, Rated from 1 (Least Desirable) to 10 (Most Desirable)

Method	Cost-effectiveness	Ease of training before use	Ease for researcher	Ease to build	Ease to move to new site	Ease to avoid canopy disturbances	Assistant necessary (N = none; U = unskilled; S = skilled)	Group size at one time	Shape of accessed area	Horizontal reach between trees (N = no; Y = yes)	Acces upperm twig (N = r Y = ye
Peconha[a]	10	9	1	10	10	8[b]	N	1–2[c]	Vertical line[d]	N	N
Ladders	8	10	9	8	5	8[b]	N	1–3[c]	Vertical line[d]	N	N
Single rope	8	8	6	9	9	8[b]	N	1–3[c]	Vertical line	N[e]	N
Tower	5	10	9	5	2[f]	8	N	1–4[c]	Vertical line	N	Y[g]
Rope web	8	6	4[h]	4	2[f]	9	N	1–3[c]	Cylinder	Y	Y
Boom	8	8	7	7	8	9	U	1	Cylinder	Y	Y
Cherry picker	2	10	10	10	5	8–9	U	1–2	Horizontal line[i]	Y	Y[g]
Crane	1	10	10	4	2[f]	6–9[j]	S	1–3	Cylinder	Y	Y
Raft	1	10	10	1	7	6	S	1–6	Cylinder[k]	Y	Y
Sled	1	10	10	1	10	6	S	2–3	Horizontal line[l]	Y[l]	Y
Walkway or tram	5	10	10	5	1–3[f]	6	N	1–10+	Horizontal line[h, m]	Y	N

Note: Our comparisons among techniques are personal opinion, but based on firsthand experience with all the methods conducted under tropical conditions. Advocates given method might argue for higher scores under certain circumstances, and scores pertaining to damage to the canopy environment may be optimistic. A range of scores co often be applied. Walkways, for instance, vary tremendously in expense depending on their length, construction materials, and intended duration of use.

[a] Can only climb trees of limited width.

[b] Damage caused mostly by frequent necessity of climbing onto branches.

[c] Even more can be accommodated by building large platforms.

[d] Very restricted to branch or tree trunk surfaces.

[e] Movement restricted to climbing on branch surfaces or ascending through areas beneath major boughs.

[f] Usually intended to be permanent or long term.

[g] Access to upper strata requires sufficient apparatus size.

[h] Robotic version under testing at Rara Avis, Costa Rica, will be an improvement.

We have compiled a brief description of many climbing techniques and summarized their attributes (Table 1). No attempt is made to describe the techniques in sufficient detail for this chapter to serve as a how-to guide. It is best to consult the primary literature (or better yet, talk with those who are currently using the method).

The peconha is a technique originated by Brazilian Indians to climb the trunks of trees up to 40 cm in diameter (Fig. 4). All that is required is a loop of webbing. Other direct trunk-climbing methods are avoided by responsible biologists whenever their use inflicts damage on trees: climbing spikes, tree surgeon's belt with spiked boots, tree bicycles or Swiss tree grippers, or boards with nails to create steps.

As an acceptable alternative, ladders can be lashed into place one above the other along the trunk with relatively few nails. Mori (1981) has used Swiss tree grippers to inch-worm up trunks, although this method should only be used on hardwoods and trees with few epiphytes on the trunk so that they inflict little damage.

Figure 4 Jay Malcolm inch-worming his way up a tree trunk with a peconha in Brazil to access his mammal traps.

Figure 5 Nalini Nadkarni assisting Jack Longino, who is climbing a tree using a moun
eering rope and ascenders.

Single rope techniques (SRT) enable researchers to sample away f
the confines of tree trunks (Fig. 5). To climb mountaineering ropes, r
people purchase rock-climbing ascenders (Perry, 1978; Whitacre, 1
Padgett and Smith, 1987), but it is also possible to replace a plain rope
a rope ladder or to design block-and-tackle systems, or even moto
chairs to make the climb less arduous. Rope webs (Perry and Willi
1981) and the boom (see Box 1) are highly modified rope-climbing n
ods that facilitate greater reach from the rope (Fig. 6).

Towers are free-standing structures that, like ropes, permit ascent
from tree trunks. In contrast, ropes can only be placed over strong
limbs, but towers can be erected anywhere and may even extend abov
canopy. Towers include an assortment of constructions, from narrow s
tures that are little more than free-standing ladders to configurations
landings every few meters that can accommodate several people.

The tower crane, developed in Panama by the Smithsonian Tropic
search Institution, is basically a tower with an arm to provide horiz
reach. It allows comprehensive access to a permanent suite of trees (
see Box 2). Researchers board a gondola at ground level and are c
upward (review in Parker *et al.*, 1992). To maneuver the gondola to
cific site in the canopy, it is usually necessary to ascend over the tree
then descend again; in this sense, approach to the canopy is from
A cherry picker is a small, relatively mobile variant of the canopy
in which the crowns are approached from below. They have been

To study reproductive aspects of tree population biology in the field, it may be necessary to carry out simultaneous or near-simultaneous studies in the crowns of several trees of the same species, which can be widely scattered through the species-rich tropical canopy. This research might involve observing between-tree visits of pollinators or seed dispersers, controlled cross-pollination experiments, or precise quantitative analyses of the synchrony of phenological events. Problems that such research may impose include the need to rapidly locate and map all reproductive trees in dispersed populations, to observe the few individuals that may flower at short notice in an average year, and to gain access to the slender outermost twigs where flowers and fruits are borne (even beyond them if fine observations or manipulations of small flowers are needed). Hands must be free to use fine brushes, forceps, and a magnifying lens.

These problems were faced in a pioneer study of the reproductive biology of rain forest trees in Malaya, carried out by six Malayan graduate students under Professors Engkik Seopadmo and Peter Ashton and colleagues at the Universities of Malaya and Aberdeen during the 1970s. Early on, it was discovered that pollination of the main dipterocarps under study took place at night, that the flowers lasted one night only, and that the whole tree population completed its flowering within two weeks, once every five years. This was not an ideal subject for a doctoral thesis, but the team succeeded, as there was a mass of flowering in the middle of the day. After three years, which gave them time to devise methods to quickly get to fine twigs at 60 m and to develop experimental techniques on specimen trees in the Forest Research Institute arboretum, a massive flowering occurred in 1976.

With the assistance of a Scottish oil-field engineer, a system of affordable telescopic booms was designed, several of which could be stationed simultaneously in the crowns of different emergent dipterocarps at short notice. Each boom consists of five lengths of standard-diameter aluminum alloy pipe: a central tube 20 cm in diameter and two pairs of longer, narrower pipes that slide into one another. One, three, or five segments can be used, and a series of holes in the pipes allows them to be locked together at several points of insertion by metal pins. The maximum length with all five segments is 20 m. Because standard-diameter pipes do not fit snugly, epoxy resin sleeves are fitted within the longer pipes, allowing a tight fit with smooth insertion.

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Box I. *Continued*

The length and angle of crown penetration required are estimated from the ground, where the boom is assembled. The booms are lifted by a steel cable that passes through a pulley attached to one of the main branches of the tree by a sleeve that does not abrade the bark. This must first be put in place by a tree climber, using SRT. One end of the cable is attached to a steel bracket near the middle of the boom, whose position can be adjusted to achieve the inclination desired. The other end of the cable is passed through a manual lifting gear attached to the base of a nearby tree.

Two ropes are attached at the lower end of the boom and, when fully lifted, are used to swing the other end into the desired position in or through the crown. They are then tied around the trunks of two different trees to anchor the boom while in use. The entire device can be lifted and adjusted into position within one hour. The researcher is attached on a block-and-tackle harness, with both hands free for research activities, and is lifted by pulling the rope through the block-and-tackle from the ground. The equipment cannot be operated by one person, which serves as an added safety precaution.

The principal inconvenience of the method proved to be carrying the boom sections through the forest, each of which needs two carriers. Transferring a boom from one tree to another within a kilometer could be done in a day by two to four people. The booms have not been used in recent years, but they still exist and await a bidder!

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successfully in dry, relatively sparse forests, where it is possible to dr
among the stand (e.g., Australian sclerophyll forests; Lowman and He
wole, 1992).

The canopy raft and sled were developed by Operation Canopee France (Hallé, 1990; Hallé and Pascal, 1992). Both the raft and sled lowered onto the canopy surface by a dirigible (Fig. 8). The raft remain
place for several days, whereas the sled—a miniaturized version of

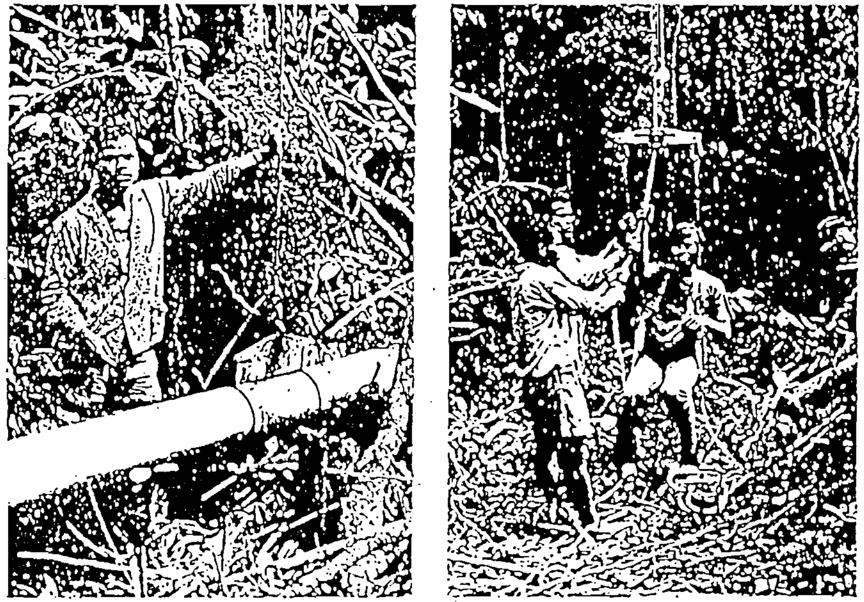

Figure 6 The canopy boom. Left: Suspension bracket at midpoint of boom from which the boom is lifted into the canopy by means of a steel cable. Right: H. T. Chán in a bosun's chair suspended from one end of the boom. (Photographs by Peter Ashton, Pasoh, Malaysia, 1975.)

raft—is repeatedly dragged over the canopy surface by the dirigible, enabling scientists to sample between many tree crowns in rapid succession (Lowman *et al.*, 1993).

Once in the trees, a common challenge is to provide a stable working area and to enlarge horizontal reach in and between crowns. At minimum, a wide branch crotch or hanging rock-climber's cot may provide comfort for short durations (e.g., Nadkarni, 1988). A more substantial approach is to construct a platform (e.g., Leighton and Thomas, 1980; Lowman and Bouricius, 1993). (The raft, crane, and some towers already have a stable "platform" built in.) Horizontal reach can also be extended away from the platform with pole pruners or long-handled nets.

Suspended walkways (Fig. 9; see Box 3) can be built in conjunction with platforms, utilizing a modular concept. They are most often reached from below by a ladder, rope, or tower, but some walkways have also been built directly out into the canopy from hillsides, circumventing a vertical ascent (e.g., Muul and Lait, 1970). Trams (cable cars) supported by steel towers

Figure 7 Researchers Solby Chavarria and Mirna Samaniego aboard the gondola suspen from the arm of the Smithsonian Tropical Research Institute's canopy tower crane in Pana

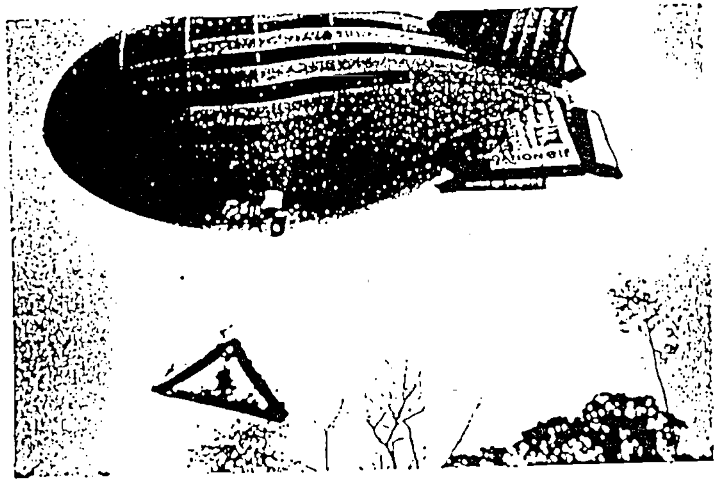

Figure 8 The raft and balloon operation, Radeau des Cimes, in Cameroon, Africa.

Box 2. The Canopy Crane

The use of standard construction tower cranes to gain access to the forest canopy was pioneered by Dr. Alan P. Smith at the Smithsonian Tropical Research Institute (STRI) in Panama. Free-standing construction tower cranes consist of a central vertical shaft, a horizontal boom that moves through 360 degrees, and an electrical motor. A gondola carrying biologists and their equipment can be delivered to any unobstructed point below the boom. Tower cranes have unique advantages for forest canopy studies: canopy access is safe, rapid, and supported from above. The same branch, leaf, or point in space can be visited repeatedly.

Tower cranes also have unique requirements. The heaviest components must be moved into position by mobile cranes or by helicopter at remote sites. Electrical demand is substantial, and a generator is required, which creates noise disturbance in the understory. It is one of the most expensive methods in which to invest. In 1990, a prototype crane with a 40-m vertical shaft and a 30-m boom was leased commercially in Panama for $2000 per month. Costs increase rapidly with the height of the vertical shaft and the length of the boom. In 1993, STRI purchased a 60-m-tall crane with a 51-m boom for $240,000. Maintenance, security, and operator costs were about $40,000 per year in 1993.

A crane has been operating over a tropical dry forest in central Panama and has demonstrated the utility of the method. Demography, herbivory, and leaf gas exchange are monitored each month for several thousand sun and shade leaves. Behavioral observations of pollinators and herbivores are also under way. Nighttime operation is routine. The stability of the gondola permits real-time *in situ* measurements. Micropressure transducers have been inserted into leaf blades to monitor water potentials at heights of 35 m. In sum, the tower crane permits the full range of investigations possible from the ground with few of the drawbacks of other techniques.

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Figure 9 · Meg Lowman and son Edward on a bridge suspended at 22 m over Blue C
Belize, as part of a walkway system built by Bart Bouricius.

can be suspended either in or above the treetops (e.g., Leonard and I
ner, 1968).

III. Logistic Considerations of Canopy Access

A. Cost of Different Methods

Why spend money at all? As just about anyone who can recall child
knows, climbing trees can be done without special equipment. Alth
the sheer physical strength required inhibits most large-bodied adults
free-climbing, native free-climbing specialists live in many parts of the
ics and work for years without injury. Yet, aspiring arborealists take war
A bare-handed approach to tropical canopy access has serious safety
backs. Tropical forests can be impressively tall, and the selection of s
climbing trees is sometimes difficult except by a professional arbori
experienced researcher. Understory species tend to be spindly with
vertical limbs, and overstory trees seldom offer branches near ground

Of the methods currently in favor today, only ropes or ladders lie w
the budgets of most students or small grants. Of moderate cost are
forms and walkways; they offer the additional advantage of creating a
manent structure, which can subsequently be used by many others.

Because equipment for the more expensive methods is durable and
mits longer work hours with proportionally larger group sizes, we u

Box 3. The Aerial Walkway Technique

Aerial canopy walkways are a relatively simple, flexible, and inexpensive method of studying a broad swath of the forest canopy. For short-term studies (e.g., a few days or weeks), structures held together and supported by ropes and high-strength industrial tapes have been used (A. W. Mitchell, personal communication). Longer-term studies will be the focus of this discussion.

For over five years, I have designed and built aerial walkways that consist of platforms and bridges linked together to form pathways through the trees. The platforms are supported by stainless-steel or galvanized aircraft cable (tensile strengths of 12,000 and 14,000 kg, respectively). The bridges are suspended from above or supported from below with these cables.

The platforms and bridges have netting and handrails made of rope or steel cable. Overhead cables and other strong attachment points are provided with safety lanyards, which allow users of the walkways to remain tethered at all times. Cables supporting bridges and platforms are bolted with galvanized steel bolts through the trees and are secured from the other side by washers and nuts. Suspending the structures on cables prevents structural members from rubbing against the tree in the wind. Trees in the walkways are also guyed with rigid seven-strand cable to stabilize and counterbalance the weight of these platforms and bridges. I do not advise encircling the tree trunks or limbs with cables or ropes to avoid risk of injuring the cambium.

I have worked extensively with a canopy biologist, Meg Lowman, to integrate both structural and scientific factors in walkway design. Factors in selection of a site for an aerial walkway include:

a. appropriateness and accessibility of the site for the specific research, education, or tourism project involved;
b. nearness of the site to ridgetops, clearings, or other physical features that may increase the incidence of lightning or wind damage;
c. placement of trees of sufficient size, soundness, and proximity to facilitate efficient and economical construction of a walkway;
d. trees that would enable future expansion of the walkway;
e. access to a range of canopy levels and trees to maximize scientific use of the structure.

Several factors affect the cost and materials that are required to construct a walkway. In the temperate zone where there is moderate to light rainfall, galvanized cable may be used as guy wires and for

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Box 3. *Continued*

structural support. In wet tropical forests or in temperate rain forest sites, more expensive stainless steel is required, at least for the main bridge support cables. Stainless-steel cable, when used for all support cables of both bridges and platforms, raises the materials cost of an average project by 15–20%. Stainless steel generally lasts for 40–50 years; galvanized cable will generally last for 20 years in temperate areas and for half that duration in moist tropical regions.

Pressure-treated wood, rot-resistant wood, or aluminum are good choices for platform decking, support joists, and bridge treads. The greater expense of aluminum plus possible metallic noise problems must be balanced against the greater weight of wood and its tendency to deteriorate more rapidly than aluminum.

Access methods to the platform include wood or aluminum ladders bolted to the tree trunks, a block-and-tackle arrangement of polyester rope and pulleys, and counterweight systems. A counterweight system requires extreme caution and extensive training in safety procedures, and can only be used by one researcher at a time.

The cost of materials for 70 m of bridge spans, four platforms (2 m × 3 m), guy wires, and a ladder or block-and-tackle for access ranges between $11,000 and $14,000 (1994 values). Labor and other costs bring the total to $17,000 to $22,000 for sites in the United States. To date, canopy research platforms have been completed at Williams College (Massachusetts), Hampshire College (Massachusetts), Coweeta Hydrological Station (North Carolina), Blue Creek (Belize), and Selby Botanical Gardens (Florida).

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took a comparison of costs on the basis of our rough estimation of perso
hours of canopy work. In our judgment, the methods in this case would b
ordered in a similar hierarchy for cost-effectiveness as indicated in Table
but the cost differences would be less pronounced because more expensi
methods often allow more researchers and longer work hours. (Obviousl
this ranking may also change with the scope of any design.) It is importa
to recognize that different researchers and different studies will have var

ing constraints. For example, canopy walkways and platforms may be ideal for long-term studies in one forest by a large group of students, whereas SRT is preferable for a study that requires examination of replicate crowns throughout a forest region.

B. Safety Precautions (with Special Consideration of SRT)

Most methods require an assistant or, in the case of the canopy raft, a skilled support staff. In addition, safety lines, backup hardware, and protective clothing are necessary.

There are many potential physical hazards in trees. For example, structurally weakened wood or the presence of fungal pathogens may be difficult to detect; epiphyte mats may slide off beneath a climber's feet; termite-infected limbs can snap unexpectedly; a young vine's grip on a tree may be more tenuous than it would appear from its size; and ants, wasps, and snakes may lurk among bromeliads.

Regardless of the method, it is prudent to carry a length of rope or webbing to tie oneself to a branch upon attaining the crown. Although no climbing technique is foolproof, in general, the more expensive the technique, the greater the security it potentially can offer. Thus, the peconha is not much safer than free-climbing and hardly less stressful, whereas when used with common sense, a tower crane appears to be very secure. Cranes and towers offer the advantage of not being dependent on the structural integrity of the canopy itself, so they can be relied on to access trees with unmanageable crown architectures or fragile wood.

For long-term success as a canopy researcher, one not only needs to *be* safe, but also must *feel* safe. Developing confidence with the methods can be difficult. For example, based on our experiences, to descend a tree with the single rope technique, we attach to the rope a simple device like a rappelling rack, which bears our weight on the way down. We loop the climbing rope into the rack, then secure the rack to our waist harness. Now for the hard part: we must work up the nerve to roll or leap off the branch. When we do, we free-fall a short distance (usually 0.5–2 m) until the rack's friction on the rope slows us. Thereafter, descent is effortless and fun. We float down as the climbing rope slithers through the rack at eye level.

Glenn Prestwich of the State University of New York (Stony Brook) had first-hand experience with the problems of treetop safety. Before his first descent, he triple-checked the rappelling rack to be sure he had strung the rope through it correctly. Unfortunately, he concentrated so intently on the rope itself that he forgot to attach the rack to his harness. Glenn made a death-defying leap, leaving the rack dangling from the rope without him.

"If I hadn't had gloves on, I'd have been in bad shape," Glenn told us. "I grabbed the rope as tightly as I could and slid 120 feet, hitting bottom fast." He hobbled off without internal injuries, although afterward he went into shock. Fourteen years later Glenn still has scars down his arms fro rope burns. We advocate careful training with professional arborists, mountaineering or caving clubs, or experienced researchers (see Laman, 1994)

C. Assembling the Apparatus

Among climbing techniques, the strategies for putting a climbing rope in place are especially varied. Heavy-gauge monofilament line is typically shot over the branch from below. For low branches, it may only be necessary to tie a stone to the line and toss it up. To reach higher limbs, biologists have used crossbows, hunting bows, slingshots, or line guns (Fig. 2). Whatever the method, the line is tied to a blunt arrow or lead weight heavy enough to propel it back to earth (Tucker and Powell, 1991). The thin line is then replaced by a parachute cord that can in turn hoist the relatively heavy climbing rope. Finally, a climbing rope is pulled over and lashed to a firm support at one end. A crossbow reportedly works best for positioning horizontal lines between trees in building walkways or canopy webs. The positioning of lines *must* be based on safety precautions, not on ease of rigging the branch.

A variant of the arborist's techniques has been devised by Dial and Tobin (1994) in which neither end of the rope is secured at the ground. The rope—which should be a brand made specifically for tree climbing—is tied into the waist harness, and the climber snaps the ascenders to the rope's *opposite* side. Because the branch over which the rope was thrown serves much like a pulley, the effort required for ascent can be considerably reduced. This works best on bare, relatively narrow branches, as these offer little resistance to rope movement.

The assembly of other methods, such as booms, cranes, and walkways, is discussed in Boxes 1–3, respectively. As it rarely takes more than 15 minutes to climb in and out of the canopy once the climbing apparatus is in place, continuous treetop visits of more than a few hours are seldom obligatory, except as a personal challenge. For protracted stays, however, a roof and space for food and toiletries may be desirable (Perry, 1986).

D. Spatial Coverage and Mobility

From a research perspective, the most crucial attributes of a climbing method are the volume and shape of the space one can enter and the permanency and mobility of the hardware.

Trunk-climbing methods, single rope techniques, and towers limit canopy access to a vertical transect line through the forest. But single rope techniques are also fairly flexible; for example, one can swing on a rope over to another tree trunk or limb, or reposition the rope once in the crown. Towers, however, can be erected above the height of the canopy or where no strong tree limbs exist to support a rope.

In contrast, walkways, bridges, and trams permit work along a horizontal transect line through the forest that can be extended indefinitely as the budget permits. They also offer vertical reach during ascent to the platform, and one can tie and descend on a rope anywhere along their span.

Solidly built towers have been the longest-lasting canopy structures, with some towers operational over many years (e.g., McClure, 1977). Built in 1958, Uganda's Haddow tower (Haddow *et al.*, 1961) still seems to be in reasonable shape (M. Moffett, personal observation), despite having been moved once and then abandoned years ago when the research projects on insect vectors ended. Some walkways and trams can likewise be classified as permanent, although they may require frequent inspection.

All climbing hardware requires regular inspection and replacement of parts as needed. Climbing ropes should never be left in the forest, but can be replaced with parachute cord between climbs to reduce exposure to the elements. Actually, ropes, ladders, or other seemingly temporary apparatuses can be climbed indefinitely without rerigging a tree if they are checked regularly and replaced as needed. Compared to a peconha, rope, or ladder, walkways and towers are awkward to disassemble and move to a new site, but it can be done given appropriate modular construction.

The most versatile methods encompass a larger volume of space, typically shaped like a wide cylinder. Of these, the simplest approach may be the boom, which can also be readily moved from one site to the next. The canopy web and canopy crane cover larger areas than a boom, but can be moved only with difficulty. A cherry picker tends to be restricted to transects along forest edges (chiefly roadsides) (e.g., Smith, 1968).

Most scientists on the French canopy raft investigate the ring of treetop foliage along the raft's perimeter. It is also possible to access any vertical ransect down from the outer edge of the raft and from some points within the raft's central area by descending on a rope. The raft is most appropriate for studies that require at most a few days at any given site, after which it is moved for logistical and safety reasons and to avoid excessive damage to the tree crowns.

The most troublesome canopy areas to study are branch tips, whether aterally within tree crowns or at the zenith of the topmost trees. The importance of this twig layer cannot be overstated for here exist most of the resources that support the canopy ecosystem: the majority of flowers, fruits, and leaves, and, at the very top of the canopy, high solar radiation for plant growth. Climbing methods that access cylindrical volumes of canopy space reach these areas most effectively. The uppermost leaves generally present he greatest difficulty, and in this regard the newest climbing innovations—he raft, the sled, and the crane—are especially effective: most of the projects involving them have centered around the topmost foliage or the boughs immediately below.

One fortuitous option for accessing branch tips is to use canoes and mc
tor boats in black- and white-water flooded forests bordering the Amazo
River and its tributaries. When the floods crest, however, the water current
can make it taxing to stay in one place for long (Darlyne Murawski, person
communication). Because the flooding is annual, these forest canopies hav
unique ecological dynamics (Goulding, 1993).

Tree trunks present their own, albeit less demanding, challenges for a
cess and study. Certain trunks may be impossible to examine by canop
crane, for example, without snapping twigs and branches as the gondola
lowered through the upper canopy. Perhaps just as troublesome, the p
conha and other trunk-based methods may physically disturb organisms o
the trunk.

With careful equipment maintenance, any climbing method permi
round-the-clock treetop visits so that different people can work at the sam
place sequentially. Methods differ somewhat in the number of people th
can be accommodated in the canopy at once (often this varies with the sit
for example, given a wide platform or enough branches to sit on, sever
people can climb the same rope in succession to work together in a tree)
The "carrying capacity" of scientists for different methods is becoming in
creasingly critical as research priorities shift from solitary endeavors to c
ordinated team projects (Moffett, 1993a). The raft operation is particular
ideal for collaborative studies (Hallé and Pascal, 1992).

E. Impact of Canopy Techniques on Ecosystems

The "perfect" climbing and research technique would enable ecologis
to examine a selected canopy volume without disturbing it, except as r
quired by experimental protocol. Yet working in tree-tops alters the env
ronment: nailed steps deface the wood; ropes slung over branches scar ba
and smash epiphytes; and as a canopy raft is lowered in place, it sna
branches and twigs beneath and stirs up the surrounding vegetation. Di
turbances range from massive, long-term physical damage to subtle, m
mentary shifts.

Certain disturbances to the canopy may have little effect on research, a
when twigs are broken during construction of an arboreal blind for a cle
view of bird behavior. The appropriateness of a technique will depend o
the species or canopy properties under study. For lack of information o
how organisms respond to the equipment, a researcher must make intuiti
decisions. For example, a walkway provides a connection between trees th
had once been isolated, alters air flow patterns all around it, and partiall
fills some of the open spaces in the forest. A crane introduces sounds th
may disturb some organisms, and the raft may alter light and moisture r
gimes. How profoundly might these changes affect the climbing or flyin
vertebrate and insect communities in that area?

The obtrusiveness of canopy techniques will become an increasingly im portant concern as the attention of canopy biologists turns to detailed studies of intact canopy structure. Rather than attempting to judge the different techniques here in relation to the magnitude of their potential disturbance—which would be premature—we describe key research directions that will be difficult to pursue without care in minimizing human impact on the canopy environment. Consider, for example, the dispersal of plants and animals in the canopy:

1. Movement Patterns in Airborne Organisms Ideally, we need to map the distribution of open spaces within the forest that are broad enough to accommodate, say, flying animals of a given wing spread, body configuration, and flight dynamics. As wing spread grows, how do the flight path options through the forest decline? For example, are large fliers channeled along wide horizontal corridors between tree strata? Are they largely confined furthermore to these specific heights by the scarcity of vertical passages bridging one stratum to the next? Or is forest stratification so ill-defined that large species are forced to fly over the canopy or at ground level, unless they can clamber across branches to get from one open pocket to the next within the trees? And how is the dispersal of the smallest airborne objects, such as spores and some insects, influenced by air currents in a forest?

2. Movement Patterns in Climbing Organisms For animals and plants (such as vines that rely on solid supports), the number of routes available through the forest must decline with increasing weight (as well as with how well the organisms cling to horizontal or vertical faces, spread their mass over several supports like a vine or snake, or bridge gaps). How does variation in architecture and woody structure (e.g., tensile strength) of the supporting plants affect route availability? And what of the position and spacing of trees and climbing plants relative to each other (e.g., crown shyness and stratification)?

We might assume that the optimal spatial scale for examining an organism's environment would increase with increasing organism size, but given the general rarity of most species of trees and other plants, and the extent of species-specific associations of insects and plants in the tropics (Erwin, 1991), even small insects may disperse long distances as part of their life-history strategies. Generalist insect species can be mobile as well. The classic example of long-distance locomotion in rain forest insects are euglossine bees that, as Janzen (1971) showed, can routinely travel kilometers between conspecific flowering plants; pollen dispersal in tropical plant species is dictated by such insects (see Chapter 19). We need to understand how insects travel through and orient long distances in the rain forest labyrinth. But what methods can we use to document such problems in an actual forest?

Broadening our questions from static forest composition to forest dynamics magnifies methodological problems manyfold. Even in the ongoing, two-dimensional, ground-based surveys such as the 50-ha plot of tree pop lation dynamics on Barro Colorado Island, Panama (Condit *et al.*, 1992), may be impossible to avoid having fragile tree seedlings crushed underfo by the surveying team and other visitors—seedlings whose survivorship d termines the distributions of the older size classes under survey. Similar within the tree crowns, each broken twig may alter the foraging patterns ants, and each scuffed branch—potentially removing any soil deposit over years as traces by rain and mist (Nadkarni and Matelson, 1991)—m alter the local prospects for epiphyte survival. Although permanent co structions such as canopy cranes and walkways seem to be ideal for lon term projects, regardless of the climbing technique, strict protocols mu be adopted. Otherwise repeated minor disturbances will culminate in su stantial (but potentially unrecognized) changes to the canopy.

IV. Canopy Access Techniques and Future Research Directions

No single method is an ultimate solution for ecological studies of th canopy. Indeed, as canopy research protocols become increasingly deman ing, more ecologists should probably stop thinking of the methods ind vidually. Instead, emphasis should be changed to combining several met ods for a more flexible approach. A good field base for canopy work woul stock the most mobile climbing equipment, such as ropes and booms, pl ground-based equipment such as binoculars and pole pruners. These su plies can be used in conjunction with more permanent structures like to ers, walkways, and cranes, chosen based on the horizontal and vertical co erage required for the projects and arranged in the forest to take be advantage of the local landscape. For example, do researchers need t reach the topmost veneer of leaves or even the open air above the canopy

Today's canopy access techniques have opened an unparalleled biolog cal frontier (Wilson, 1991; Moffett, 1993b; Lowman, 1995). Before the de velopment of these techniques, as rain forest pedestrians, people were da zled by the silhouettes of exotic vertebrates and herbage above. Now a climbers with the canopy at our fingertips, smaller organisms materializ before us to enrich our image of the canopy's lavish ecological tapestry. An if we seek out animalcules hidden from us by size, and larger beings tucke from view within canopy soil or behind leafy veils and palisades of bark an wood—what then? We will have barely scratched the surface of the canop as the earth's grandest expression of organic life. In the next few years th energies of arboreal biologists will hopefully shift more and more from th problems of canopy access to those of data collection within the treetop' ecological labyrinth.

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