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AN UPDATE ON LOW-TECH METHODS FOR FOREST CANOPY ACCESS AND ON SAMPLING A FOREST CANOPY

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ABSTRACT. Research interest in canopy processes, particularly in tropical rain forests, has increased substantially in recent years both as a consequence and cause of a wide range of canopy access techniques. Recent developments in low-tech canopy access methods are described which increase versatility of access and extend sampling capability. There follows a discussion of sampling issues in canopy research, including demonic intrusion, systematic error, pseudoreplication, non-random sampling, and the problem of working in three-dimensions. In conclusion, possible improvements in canopy sampling capability are suggested, particularly with respect to further increases in access flexibility, development of better sampling strategies, and increased communication of protocols by canopy researchers.

INTRODUCTION

Though elusive, the forest canopy is increasingly recognized by researchers as complex, important and in urgent need of study. As a result, there have been several important developments in access techniques (Moffett & Lowman 1995). As access methods have become more widely available and as an awareness of them has increased, research opportunities and output have grown (Nadkarni & Parker 1994, Nadkarni & Lowman 1995). Following some important initiatives such as recent symposia, canopy scientists have become much less isolated, and there has been a corresponding increase in the transfer of information on practical aspects of their research (e.g. Lowman *et al.* 1995).

Until recently, there had been a hiatus in the flow of information on canopy access methodology. There have been publications on single rope technique (SRT) in the late 1970s and early 1980s (Perry 1978, Perry & Williams 1981, Whiteacre 1981) and a handbook on access methods (Mitchell 1982), which has been out-of-print for several years. More recently, the scope and significance of canopy access has been described in books (Mitchell 1986, Moffett 1993a) and reviews (Heatwole & Higgins 1993, Lowman & Moffett 1993, Lowman *et al.* 1993, Moffett 1993b, Moffett & Lowman 1995, Barker & Sutton 1997). However, relatively few publications have appeared providing new information on practical aspects of access techniques, (but see Dial & Tobin 1994, Lilly 1994, Laman 1995, Mori 1995). Canopy access techniques are in need of constant revision as technical innovations become available and as researchers explore the limits of existing methods. Consequently, it is important that potential or existing canopy scientists are aware of the growth and capability of access techniques, so that they may fully exploit them. Choice of access and sampling techniques are dependent on many factors, including access costs and availability, sampling time (Zandt 1994), forest type (Moffett & Lowman 1995) and the researcher's experience.

Despite, or perhaps because of, the increased range of canopy access methods, the researcher is now confronted with the challenges of deciding on the most appropriate access method from the wide range available and on which sampling strategy to adopt. The need to develop sampling methodologies that are consistent between canopy studies (Lowman *et al.* 1995) and which are statistically-rigorous is recognized now that scientists have, to some extent, been liberated from concerns about access.

The purpose of the first part of this paper is to provide an update on low-tech methods of canopy access currently available for researchers. In particular, aspects of existing methods are described which have apparently not been published in detail previously. The update has resulted from personal experience during hundreds of climbs in Borneo and from communications with other canopy researchers who use low-tech access methods. In general, the updated techniques described here have arisen from the need, frequently experienced by canopy researchers, to safely increase the flexibility of their access technique, and to extend the range, duration and reliability of their sampling. The second part of the paper describes a range of sampling problems particularly associated with canopy research.

Low-tech methods for canopy access

The term low-tech is used here to refer to techniques which are often suitable for research-

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ers working individually, which employ relatively simple equipment, are associated with comparatively low purchase or running costs, and are highly mobile (see also Barker & Sutton 1997). Such techniques may be the main canopy access technique. Low-tech methods may also be used in conjunction with high-tech options, such as with towers, walkways, cranes and aircraft (e.g. Moffett & Lowman 1995). Low-tech methods are almost inevitably less secure than high-tech systems, but safety precautions must always take priority over research needs (Moffett & Lowman 1995, Laman 1995). It is *essential* that, before implementation, any new access techniques are learned with supervision from an experienced climber and are practiced near the ground.

The simplest, safest and often most effective low-tech canopy access methods are ground-based. Examples of such methods are described elsewhere (Moffett & Lowman 1995; Ingram & Lowman 1995; Barker & Sutton, in press) and are listed in TABLE 1. In the remainder of this section, innovations are described in the two main types of canopy-based, low-tech method: bole-climbing and rope-climbing.

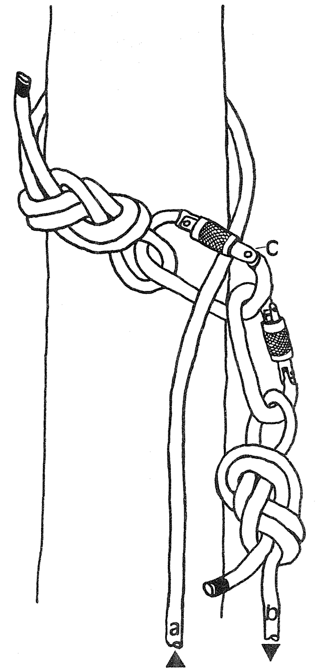

FIGURE 1. Detail of a remote belay-release, used for retrieving a support rope from below. When rope is pulled at 'b', the support rope, 'a', is pulled through the caribiner at the belay. Note the 'figure-of-eight' knots. The upper caribiner, 'c', bears the weight of the climber when the support rope is being used for climbing.

Bole-climbing methods

The main bole-climbing methods utilize simple equipment including the foot-loop, or *peconha* (Moffett & Lowman 1995), French spikes (Mori 1995), tree bicycle (Mori 1984) and ladders (Mitchell 1982). The advantage of these methods is that they can often be used for rapid ascent and hence allow the sampling of numerous trees (TABLE 1).

Another simple bole-climbing method, not widely referred to, involves a waist and tree sling (nylon bands, or prussik lines) around the tree bole (Donahue & Wood 1995). The climber is always attached to at least one sling, via a waist harness. The climber's weight is supported by one sling, while the other is lifted farther up the bole. The climber then transfers his/her weight to the upper sling and repeats the procedure. This technique, which is suitable for trees up to ~1.5 m in diameter (Donahue & Wood 1995) is safe and effective, though some users report that it is slow, laborious and uncomfortable (Dial & Tobin 1994).

Because bole-climbing methods are already simple, there is only limited scope (or need) for their improvement. However, both safety and efficiency can be increased by incorporating some additional equipment. For example, the safety harness and safety-line are not explicitly required for use with the foot-loop or with ladders, but their use is strongly recommended. Safety harnesses and lines can either be of the lightweight kind used for caving and mountaineering (e.g. Meredith & Martinez 1986) or the heavier type used by foresters, tree surgeons and arborists (see Dial & Tobin 1994). A strap or rope passed around the bole, either throughout the climb or only during stops, is attached to the waist harness. Apart from restraining the climber in the event of a fall or when the climber needs to rest, a harness can also be used to attach equipment and to free hands for experimental work.

Another hybrid technique, which can increase the effectiveness of any bole-climbing method, is to use ropes for descents. Having completed the climb, descent can be achieved either by reversing the bole-climbing technique, or by abseiling (rapelling) down a rope that has been carried or hoisted up. Bole-climbing equipment, such as spikes, tree grippers or sections of ladder, can either be carried down with the climber or lowered separately. There are two ways of anchoring (belaying) the fixed end of the rope before the descent. One approach is to loop the rope over a stout branch near the point of de-

TABLE 1. Summary of the sampling implications of various canopy access techniques. Each category is given symbols representing high (●●●), intermediate (●●) or low or zero (●) sampling constraints. Canopy researchers can often reduce sampling constraints by using access techniques in combination.

	Sampling constraints									
Access technique	Purchase/establishment costs	Running costs per researcher	Dependence on structural integrity of forest	Possibility of demonic intrusion	Possibility of pseudoreplication	Possibility of biased sampling	Difficulty reaching upper or outer canopy	Restriction to a particular forest/site	Restrictions on prolonged sampling	Restriction to narrow range of sample types
High-tech										
canopy crane	●●●	●●●	●	●	●	●●	●	●●●	●●	●
tower	●●	●	●	●●	●●●	●●●	●	●●●	●	●
scaffolding	●●	●	●	●●	●●	●●	●●	●●	●	●
walkway	●●●	●	●●●	●●	●●	●●	●●	●●●	●	●
cherry picker, boom	●●	●●	●	●●	●	●●	●●	●●	●●	●
canopy raft	●●●	●●●	●●●	●●●	●	●●	●	●●	●●	●
aircraft: dirigible, ultra-light	●●●	●●●	●	●●	●	●●	●	●	●●●	●●
Low-tech										
(a) *ground-based:*										
natural treefalls, branchfalls etc.	●	●	●	●	●	●●	●●	●	●	●●●
causing trees, branches, etc. to fall	●	●	●	●	●	●●	●●	●●●	●	●●●
insecticide fog	●	●	●	●●	●	●●	●	●	●	●●●
net, pole-pruners	●	●	●	●	●	●●	●●●	●	●	●●
raising equipment on pulleys	●	●	●●	●●	●●	●●	●●●	●●	●	●●
binoculars, radiotracking	●	●	●	●	●	●●	●	●	●	●●●
hemispherical photography	●	●	●	●	●	●	●	●	●	●●●
(b) *bole-climbing:*										
ladder	●●	●	●●	●●	●●	●●	●●●	●	●●	●●
spikes, tree grippers, leg irons	●	●	●●	●●	●	●●	●●●	●	●●●	●●
foot loop, waist/tree slings	●	●	●●	●●	●	●●	●●●	●	●●●	●●
(c) *rope-climbing*	●●	●	●●	●●	●●	●●	●●●	●	●●	●●
(d) *others:*										
observation platform	●	●	●●	●●	●●	●●	●	●●●	●	●●

scent. One end of the rope must be secured at ground level, either before commencing the ascent or afterwards, by an assistant on the ground. The other method, which can be used with a stout branch or simply the bole itself, is to belay the rope at the point of descent. The problem of retrieving this rope from the canopy after the descent is avoided by using a second rope or a cord to release the rope and pull it to the ground. I refer to this technique as a remote belay release (FIGURE 1). The belay, though temporary, is safe because it can only be taken down when the climber's weight is no longer pulling down at 'a'. The use of the locking carabiners (shown in FIGURE 1) allows for quick assembly or disassembly of the belay. To reduce the unlikely possibility of the upper carabiner ('c', in FIGURE 1) opening prematurely while under stress, the researcher can add a second carabiner immediately adjacent to the existing one (with the opening facing in the opposite direction). Alternatively a screwlink (e.g. Maillon-type) can be used instead of the upper carabiner.

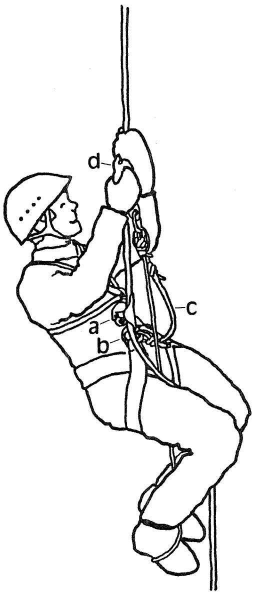

FIGURE 2. The use of the single rope technique (SRT) for canopy access (European configuration). The chest ascender, ('a'), is secured to the waist harness by a screwlink ('b'). Also attached to the screwlink is a cowtail ('c'), which is seen here temporarily but securely attached to the foot ascender ('d'). (Diagram courtesy of Petzl Sa., France).

Single rope techniques

Rope techniques have provided a very important means of canopy access for researchers (Lowman & Moffett 1993, Moffett 1993a, Nadkarni & Parker 1994, Laman 1995) and allow access to parts of the canopy away from the bole (Moffett & Lowman 1995). Many canopy researchers use rope techniques as their main access method, as a safety backup, or in combination with other access methods. Two generic terms, single rope technique (SRT) and arborist technique, have been used for rope methods. Although the terms are sometimes used synonymously, there are important differences in both equipment and technique.

The more widely-used and familiar method among canopy researchers is SRT (see Mitchell 1982, Laman 1995), which is derived from mountaineering and caving techniques. SRT generally utilizes, at least for the main ascent and descent, a long (e.g. 100 m) rope, one end of which is anchored at ground level. The arborist technique (Dial & Tobin 1994, Lilly 1994), developed by professional and recreational tree climbers, usually employs a shorter (e.g. 50 m) rope. The rope is not anchored at ground level but, instead, is attached at both ends to the climber's harness. One end of the rope provides support. The other end is live and free to be pulled though a locking knot or ascender. This action causes the climber to ascend the live rope, which is supported above by a stout branch, acting as a kind of pulley. The advantage of the arborist technique, which is fully described by Dial and Tobin (1994), is that the climber can easily move within, or even between, tree crowns since the rope is not anchored at ground level. The remainder of this section will emphasize SRT although, for movement within tree crowns, SRT can be modified using arborist-type methods.

Personal equipment for SRT includes a waist- (sit-) harness and a chest-harness, both of which are attached to a chest ascender (FIGURE 2). The chest ascender and foot ascender alternately bear the climber's weight during the ascent. The arrangement of ascenders shown in FIGURE 2 is favored by European climbers and differs from the method used by many U.S. canopy researchers (see Perry 1978, Laman 1995), and is probably more efficient. The SRT waist-harness is typically lighter and cheaper, but also less comfortable, than the utility harness favored for the arborist technique. Basic SRT equipment should also include a descender, preferably of the auto-lock type. It is useful to carry at least two spare tape slings for anchorage in the canopy, as well as spare descender, ascender and carabiners. I see no advantage in adopting home-made harnesses and prussik knots advocated by Whiteacre (1981), or the arborist knot, described by Dial and Tobin (1994), except as a back-up. Additional safety equipment should include one or two cowtails, which are short lengths (e.g. 50 cm, 35 cm) of 11 mm diameter rope attached to the sit-harness by a screwlink (Maillon). The screwlink functions like a carabiner, but is safer for more permanent attachments because it cannot be opened accidentally. The free end of each cowtail carries a carabiner. These form temporary, secure attachments, such as to the foot ascender during a climb (see FIGURE 2), so that a failure of the chest ascender would probably not result in a fall. A cowtail can also act as a safety line by clipping onto temporary anchor points (e.g. slings) in the canopy, especially when transferring between support ropes (see below).

Rigging trees with ropes

For any rope technique, the rope itself needs to be chosen and used with care. Ropes should be low-stretch (static) and constructed from nylon or polyester kernmantle. Such ropes have a relatively thick outer sheath that resists abrasion, which is particularly important if the researcher is employing the arborist technique. The stretchable dynamic ropes used by mountaineers are not suitable for any canopy access method since they make long ascents extremely tedious, and descents can be difficult to control and dangerous near the ground. For SRT, rope diameters in the range 9–11 mm are recommended. Larger-diameter ropes are likely to have a longer working life, but smaller-diameter ropes are easier to carry long distances through the forest and are often easier to pull up into the canopy. A suitable rope length for most canopies is 120 m, sufficient to climb trees up to about 50 m tall.

Various methods exist for rigging trees with ropes and are described elsewhere (Perry 1978, Mitchell 1982, Dial & Tobin 1994). Most methods involve using a cord (e.g. nylon, 2–3 mm diameter) to pull the rope over a potential support branch. The cord itself can be pulled up by weighted fishing line (e.g. 7.5 kg monofilament) that is fired over the branch using a slingshot, crossbow, rifle or even a fishing rod (Mitchell 1982). Other methods, that employ cord rather than fishing line, use a throw bag (Dial & Tobin 1994) or other weighted devices (Lilly 1994). All these methods are difficult when target branches are high, or when they are obscured by understory vegetation. However, these problems can often be overcome by working from adjacent trees, or by rigging a target tree in stages, rather than attempting to place a rope high in the canopy from the outset. These techniques also allow a closer examination of potential support branches before they are used. An alternative approach for tall trees is to use a line-throwing device. These send missiles capable of pulling fairly heavy cord into the canopy and use rifle blanks (e.g. 'E-Z Line Thrower', Speciality Products Co., Queenstown MA, USA) or compressed air (e.g. Plummett, Burgess Hill, RH15 9LD, UK). The choice of line-throwing devices may be partly determined in some countries by restrictions on the import, local availability or use of weapons and blank ammunition, which airlines do not generally allow on flights.

To increase flexibility, the cord used to raise the rope can be left in position until needed (Perry 1978) as, for example, when several trees are rigged before sampling begins. This approach avoids dedicating a rope to a single tree. It also allows the rope to be taken down regularly for inspection and storage in studies where climbing is intermittent. If the cord is tied into a loop, the rope can be attached to the cord and pulled up from either side of the support branch. Also, if the rope becomes prematurely detached from the cord, the procedure can usually be repeated without difficulty.

Reaching the outer canopy with SRT

Simply climbing up to a support branch by SRT is a very limited form of canopy access for two reasons. Firstly, the initial support branch will often be one of the lowest in the crown since these are the easiest to reach when rigging the tree. Secondly, sampling in canopy research frequently occurs within the crown itself, especially at the periphery, where flowers, leaves and insects are predominantly located. Using SRT in an unmodified form, the researcher will find it difficult or impossible to reach the distal parts of branches (Nadkarni & Longino 1990, Lowman *et al.* 1993, Moffett & Lowman 1995). However, there are several ways of extending the sampling range of SRT beyond the main rope. The simplest approach, also suitable for bole-climbing techniques, is to use nets, pole-pruners, or pole-saws with extensible handles. Clearly, tools with cutting edges must be kept well away from any support ropes. However, using very long handles can be difficult, especially for lateral sampling, because of problems with weight and maneuverability. A further problem with remote sampling is that it does not allow the researcher to make *in situ* measurements or observations, for example in studies of leaf physiology, pollination mechanisms or undisturbed microhabitats.

In many cases, the researcher needs intimate access to the outer canopy which is not possible with remote sampling techniques. One method for gaining access to tree crowns using SRT is to work from an adjacent tree. A more elaborate technique is to work from a system of ropes attached to other trees (Perry & Williams 1981). Both of these approaches require the use of support trees which are taller than the target tree. Emergent trees are often particularly suitable as support trees, especially if main supporting branches are above the intended sampling area. However, this approach is not suitable if sampling is to take place in emergents themselves.

A further option for increasing the flexibility of SRT for close sampling of the canopy is to leave the main rope using arborist-type methods that utilize shorter lengths of rope in the canopy itself. During the transfer, the climber *must* be secured via at least one safety line to the tree. If a strong branch is available to stand on beneath the support branch, the climber's weight can be taken off the rope. Only then can the ascenders be removed (see Laman 1995). However, the support branch may be the lowest branch, simply because it was the easiest branch to shoot the initial line over. If this is the case, it is possible to make an alternative support by securing a loop rope so that it hangs under the support branch. Although it is physically arduous, I have used this method successfully many times. Again, at least one safety line must be used while climbing onto the support branch.

Moving around within the canopy can be achieved safely using short (e.g. 10 m) lengths of rope thrown over a higher branch (*sensu* Whiteacre 1981, Dial & Tobin 1994). Two such ropes (e.g. 9 mm diam.) can be carried in a small rope bag. In this modified SRT approach, one end of a rope is belayed onto the tree bole while the climber ascends the other, which *must* have a stopper knot near the end (see below). If there is any doubt about the load-bearing capacity of thinner, higher branches, this method should not be attempted. Higher parts of the tree itself can be climbed at the bole, using branches. The researcher should always be belayed onto the tree, using at least one safety line. A second safety line is positioned higher before moving the first line higher still. Movement outwards can be achieved by walking on sturdy branches, supported from above by a taut rope, using a high anchorage point for maximum stability (Lilly 1994). Lateral movement can also be achieved in a method described by Whiteacre (1981) using running belays.

The canopy researcher is most at risk when commencing an ascent or, particularly, descent. These are the periods during a climb when equipment is initially brought into use and when there is most uncertainty about its reliability. Having left the main rope, the researcher can descend back down the canopy part of the tree by abseiling down a short (e.g. 10 m) rope. However, it is *essential* that a stopper knot has previously been tied near the end of this rope, to prevent accidentally abseiling off it. The knot must be large enough so that it will not pass through the descending device, and there should be at least 60 cm of rope beyond the knot for added security. A second rope can be used for a remote belay release (see FIGURE 1) once the climber is safely anchored at, or near, the main rope.

It is important, if leaving the main rope, that the climber knows which side to descend. Descent must be on the opposite side from the anchored side, which can be checked by firmly pulling on the rope. This is necessary, in any case, to take in the elastic slack generated when the climber previously left the main rope. A safety line should be used to attach the climber to the tree whilst transferring back to the main rope, and this should be retained until the climber is confident that the descender is attached correctly. Alternatively, the climber can initially re-attach to the main rope using ascenders, before transferring to the descender device (see Laman 1995). It is essential to practice these transfer techniques near the ground before ascending to the canopy. Despite the complications and increased risk of leaving the main rope, it can be a useful procedure for moving higher into the tree. It also allows the researcher to move the main rope to a more convenient or safer location in the tree, assuming that there is excess rope length available. The descent side of the rope can be pulled up by the researcher and passed over an alternative support branch. If there is any doubt about there being sufficient rope available to reach the ground from a higher branch, a stopper knot should be used. It is a distinct advantage if there is a competent assistant on the ground who can, if necessary, untie and retie the rope and check its position after it has been moved.

Sampling

The emphasis in the preceding sections has been on techniques that enhance the flexibility of low-tech canopy access methods. Improvements have also occurred in the versatility of high-tech access methods (see Moffett & Lowman 1995). With an increase in flexibility in access to the canopy, the options available for obtaining samples have expanded. Some new access methods, such as the crane, now allow much greater sample sizes than the "chronically small" samples collected by other access methods (Zotz & Winter 1996). Canopy researchers may now more easily adopt statistically-robust experimental designs and use appropriate replication, depending on the access method. Sampling constraints of various canopy access methods are summarized in TABLE 1. More general advantages and disadvantages of the main access techniques are given elsewhere (Lowman *et al.* 1993, Moffett & Lowman 1995). In the discussion which follows, some remaining sampling problems, which seem to be particularly associated with canopy research, are outlined. Finally, some suggestions for improved sampling practices are presented.

Limitations on sampling capability

The word sampling is used here to refer to any method of data gathering that includes collecting, making observations and destructive and non-destructive measurements. A sample is a subset of the population being studied, whether it be insects, leaves, epiphytes, flowers, tree crowns, vines, or all possible locations of a light or humidity sensor. The type of sample replicate used will be determined by the way in which the study fits into a forest hierarchy. For example, many physiological measurements can only be made at the leaf or shoot level, while architecture determinations usually involve an entire tree, and canopy-atmosphere gas exchange measurements occur at the stand level (see Cermák 1989). Statistical comparisons can be made between populations or, more usually, replicated samples of populations. It is important that replicates are independent (see Hurlbert 1984), obtain a desired level of precision, and are also sufficiently numerous to accommodate spatial heterogeneity in the environment. In practice, this is sometimes difficult to achieve in canopy research.

In some earlier canopy studies, difficulties with access limited the options for sampling and, therefore, experimental designs. Statistically-valid sampling of the outer canopy has been particularly difficult (Lowman *et al.* 1993). However, sampling problems may also exist when access is easier, for instance when sampling the sub-canopy from towers, walkways and from single trees accessed by SRT. This is because such methods often provide only one fixed sampling position. Stationary canopy access points constitute a single independent sampling platform (Schowalter 1995) and repeated samples from one such position cannot provide information on variation on a stand or landscape scale. In several published canopy studies using a tower, ladder or rope access method, a single tree was used. If the tree is considered to be the unit of replication, sample sizes in such studies may effectively be one. To obtain information on variation among samples, within-tree replicates such as leaves have been used, though they are probably not statistically independent and are therefore pseudoreplicates (see Hurlbert 1984). Another limitation of static access points is that insufficient sample material may be accessible when destructive sampling is being used (e.g. Reynolds & Crossley 1995).

A further problem is that the positioning of access systems is often non-random and opportunistic. Support trees of a walkway are selected because they are large and a certain distance from other support trees (Lowman & Bouricius 1995, Reynolds & Crossley 1995). Access by SRT is generally limited to large, healthy trees with convenient branches. Towers are necessarily located in canopy gaps (Parker *et al.* 1992). The presence of emergents and gaps may influence where a canopy raft is sited. In all these situations, ultimate positions of sampling points may be unrepresentative, limited in number, or simply inconvenient. Because of sampling constraints in the canopy, some ecological studies may in fact be autecological simply because the crowns of only one species of tree can be reached from the access platform. A potential limitation of this approach is that the species used may not be representative.

Another problem, analogous to Heisenberg's uncertainty principle, is the possible effect of canopy access methods themselves on the canopy. This issue, which has only recently been adequately addressed (Moffett & Lowman 1995), may impose constraints on the scope and quality of sampling. Examples of this include the disturbance of canopy microclimate by the canopy raft (Koch *et al.* 1994, Parker *et al.* 1992, Moffett & Lowman 1995), the possible effect of canopy walkways on movements of arboreal animals (Perry & Williams 1981) and the obstruction of potential sampling positions by the canopy access structure (Hollinger 1989). In other words, access methods can be a form of demonic intrusion. This is a problem quite separate from that of damage to the canopy since, for example, branches broken by the canopy raft and a crane's gondola or epiphytes dislodged by ropes may not be the subject of study. A further problem is that the effect of access structures on the sampling environment may differ according to the method being used. For example, the vertical distribution of forest light may be substantially different when measured from a tower or from a crane's gondola (see Chazdon *et al.* 1996). Such discrepancies are likely to impose difficulties in comparative studies using different access techniques.

Canopy researchers have frequently identified access per se as a major limiting factor in their work (Nadkarni & Parker 1994). However, few researchers have specifically acknowledged the problem of canopy sampling constraints (but see Kapos *et al.* 1993, Koch *et al.* 1994, Baldocchi & Collineau 1994, Schowalter 1995). In some (perhaps many) cases, potential sampling difficulties have been overcome. In other studies, systematic error (bias) or pseudoreplication is evident but is not referred to. Obviously, working in the canopy imposes real difficulties. However, if the experimental design has been compromised because of access difficulties, this should be clearly stated by the researcher or, better still, avoided at the outset. There is no reason why canopy scientists should apply less rigorous design criteria than their terrestrial colleagues.

Finally, canopy researchers need to confront the complexities of working simultaneously in both horizontal and vertical dimensions. Aside from the difficulties of sampling in three-dimensions, researchers also have the challenge of representing results in the two-dimensional medium of publications (Nadkarni & Parker 1994). Traditionally, data have often been presented as profile diagrams (Richards 1983) in which three-dimensional information is lost. Another aspect of three-dimensional sampling is the almost inevitable introduction of a temporal dimension. For example, the variable being measured may fluctuate in a heterogeneous canopy environment (e.g. Baldocchi & Collineau 1994), and this could be a problem given the added time required to move between sampling points in the canopy (Kapos *et al.* 1993). Canopy samples may, therefore, potentially occur in a four-dimensional hyperspace. Hence, certain investigations may simply be impractical in the canopy.

Prospects for improved sampling design

Despite the sampling difficulties referred to above, improvements continue to be made, particularly in access flexibility, sampling strategies and in communication between canopy scientists. Flexibility in the use of canopy access methods is a major means of increasing sampling capability, particularly in avoiding sampling from static access points. One approach is for researchers to be adaptable and, if necessary, to further increase flexibility by using more than one access method. In fact, this is the case for most canopy researchers (Nadkarni & Parker 1994). Another option is to introduce new techniques such as the highly-maneuverable canopy sled, attached to a dirigible that allows insect sampling in replicated transects over the canopy (Lowman *et al.* 1993). High-tech access methods which are versatile and dynamic, such as cranes and aircraft, provide considerable sampling capability and are under continuous development. Low-tech methods offer flexibility because they can be used in combination with other methods and because they are generally highly mobile. Hence, many low-tech methods can be used to avoid pseudoreplication (TABLE 1). Such methods are also relatively inexpensive, allowing the possibility of multiple sets of equipment within a project and, therefore, the prospect of simultaneous sample collections by more than one researcher.

There is a continuing need for canopy researchers to address the potential problems of bias and pseudoreplication. Protocols can be developed to reduce or remove bias in within-tree sampling such as by randomized branch sampling to estimate total foliar area, fruit mass or woody dry mass, insect egg or larval populations (see Gregoire *et al.* 1995, Zandt 1994). If canopy leaves are sampled, the population will be heterogeneous because of ontogenic or microclimatic effects (see Harper 1989). Thus, it may be necessary in some studies to make additional measurements to provide information on microhabitat variables within a sampling site. If within-tree sampling is conducted, assumptions concerning the independence of replicates should be made clear (e.g. Barker & Booth 1996). For example, individual branches can sometimes be regarded as being autonomous for water relations (Sprugel *et al.* 1991), carbon economy or herbivory (Watson & Casper 1984). In such cases, leaves taken from different branches can be treated as independent and not as pseudoreplicates. Tree architectural studies may have much to offer in determining which (if any) structural units within a tree canopy can be considered independent for sampling purposes.

The choice of canopy access should be appropriate for the sampling frequency and type of sampling equipment being used. For example, SRT or bole-climbing techniques are difficult to use in conjunction with heavy or delicate equipment, and when the researcher needs to spend long periods in the canopy. The frequency of canopy sampling will often be determined by the type of measurement being made. For example, leaf physiological studies may ideally require sampling at one-second intervals for net CO_2 uptake and stomatal conductance measurements, but daily carbon gain measurements every hour (Zotz & Winter 1996).

Canopy researchers may increasingly need to incorporate cost/benefit analyses into experimental designs (*sensu* Zandt 1994). High-tech static access methods (towers, walkways) have high initial costs. However, once established, these structures continue to be available for a succession of researchers who can often also use the access in groups and for prolonged sampling without further cost (Moffett & Lowman 1995). However, the dynamic high-tech methods (crane, canopy raft) incur costs throughout their operation, and may be prohibitively expensive for graduate students on small grants. Cheaper, low-tech methods may be prohibitive instead for some studies in terms of sampling capability.

Techniques are becoming available which describe or quantify the three-dimensional canopy environment. Foliage distribution in an Indonesian forest was determined using a camera mounted on a rope and pulley (Koike & Syahbuddin 1993). Occupation of lianas in three-dimensional space was plotted by a mapping technique in Mexico (Castellanos *et al.* 1992). Light distribution in vertical and horizontal planes in Malaysia was described in an isogram (Yoda 1978). A three-dimensional sampling volume can be defined by four vertically-stretched cords (Hollinger 1989). Canopy surface position was determined using a canopy crane in Panamá (Parker *et al.* 1992). Vertical (two-dimensional) forest profiles can be accompanied by ground plans (Richards 1983) or other horizontal projections, though this is rarely done (but see e.g. Parker *et al.* 1992; Koop & Sterck 1994). Reasons for the lack of such information include the need for additional measurements and also simply convention. Three-dimensional aspects of forest structure are important because of their influence on microclimate and animal food resources (Richards 1983). Consequently, there is likely to be an increasing need for researchers to quantify three-dimensional attributes. Canopy researchers will, therefore, need to develop skills in data handling and graphical presentation (see Nadkarni & Parker 1994). The development of modeling (e.g. Koop & Sterck 1994) and imaging techniques (D. Vieglais, pers. comm.) will allow increased use of quantitative, rather than simply descriptive, representations of the three-dimensional forest environment.

Further improvements in access flexibility and in sampling capability will be implemented more effectively if information is properly dissipated within the community of canopy researchers. Canopy scientists, few in number and often geographically-isolated, have begun to communicate more effectively with each other (e.g. Nadkarni & Parker 1994, Nadkarni & Lowman 1995, Lowman *et al.* 1995). Increased communication is essential in developing and implementing standardized protocols, particularly in comparative studies (Nadkarni & Parker 1994, Nadkarni & Lowman 1995, Schowalter 1995). Increased integration of canopy research results (for instance, under the aegis of *Selbyana*) has been proposed (Nadkarni & Lowman 1995). However, publication in a journal dedicated mainly to canopy research may not be appropriate for papers intended primarily for a different readership. It therefore seems inevitable and preferable that the more specialist papers continue to appear in widely disparate journals. The availability of such publications to the canopy research community could, however, be improved if such terms as canopy access, canopy sampling or forest canopy were routinely included in the keywords. Given the continuing difficulties of both canopy access and sampling, there is a clear need for canopy researchers to be explicit in describing the limitations and innovations of their methods.

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