Selbyana 15(2): 38–50

A PROFILE OF FOREST CANOPY SCIENCE AND SCIENTISTS—WHO WE ARE, WHAT WE WANT TO KNOW, AND OBSTACLES WE FACE: RESULTS OF AN INTERNATIONAL SURVEY

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ABSTRACT. Forest canopy communities are important in maintaining the diversity, resiliency, and functioning of the ecosystems they inhabit. With the increasing interest in and amounts of data on forest canopies that are resulting from new access techniques, ecologists require tools to deal with: 1) new types of data, 2) a great deal more data, and 3) the necessity of sharing data among researchers who have separate research questions. With the support of the National Science Foundation, we established the Canopy Research Network (CRN) to bring together forest canopy researchers, quantitative scientists, and computer scientists to develop methods to collect, analyze, and interpret three-dimensional spatial data relating to tree crowns and forest canopies. By means of a survey to canopy scientists, we compiled an array of research questions and a set of potentially applicable information models and software tools that are in use in allied fields. We found the young field of canopy science to be somewhat fragmented, with a tremendous range of questions spanning wide spatial scales and approaches. Canopy scientists have a wide range of tools available for access and data analysis, but few avenues for formal communication and synthesis among disciplines. There appears to be little overlap in use of software programs; respondents cited the use of 29 different software programs, 31 statistics packages, 31 statistics packages, 13 GIS programs, and 23 other software programs. Information on canopies is published in 72 journals, communicated at 17 different meetings, and informally exchanged via 13 electronic mail bulletin boards. To more easily overcome perceived obstacles, canopy scientists must find methods to more efficiently exchange ideas and information.

INTRODUCTION

Organisms and processes of tree canopy communities contribute to the maintenance of the diversity, resiliency, and functioning of forest ecosystems. The forest canopy is defined as "the combination of all foliage, twigs, fine branches, epiphytes, as well as the interstices in a forest". Forest canopies are hypothesized to contain a major portion of the diversity of organisms on Earth as well as constitute the bulk of photosynthetically active foliage and biomass sinks for carbon. In the last decade, a remarkable burgeoning of scientific interest in the canopy has occurred. The number of scientific publications on canopy structure has grown at a disproportionately rapid pace relative to the general field of biology (FIG. 1). Aspects of the canopy have been the focus of many recent symposia, scientific books (e.g., Benzing 1990, Russell *et al.* 1989, Lowman and Nadkarni, In Press), and popular articles and media. This attention is a consequence both of new techniques for canopy access (e.g., hot air balloons, construction cranes), and of growing concern for conservation issues such as biodiversity, global atmospheric change, and preservation of tropical rain forests.

Both the types and amounts of canopy structure data are changing rapidly. Historically, quantitative estimates of the complex nature of the canopy were restricted to ground-based surveys, (e.g., Ford 1976) or tree-based studies with small numbers of replicate trees (e.g., Nadkarni 1984). In the past, the simplicity of rope-climbing generated studies by scientists who worked singly or in small groups and which produced fairly small data sets. However, the ease with which recent access innovations such as the canopy raft (Hallé 1990) and the canopy crane (Parker *et al.* 1992) permits multiple teams of scientists to work within the same volume of the canopy and results in complex and expensive data sets that must be used jointly. These investigations require spatial information on the underlying substrate (tree trunks, branches and foliage) for its own sake and to relate forest canopy data to allied data sets. Data collected by canopy research teams will be useful to other scientists (e.g., geographers, land use managers), just as data emanating from allied fields could aid forest

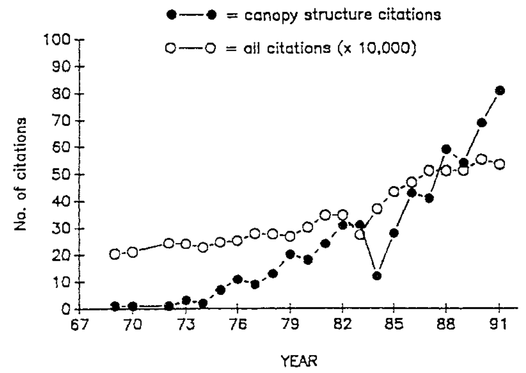

FIGURE 1. Indication of the rate of scientific literature published on canopy structure compared to the rate of literature published in the general biological literature. Data points are the number of citations with keywords related to canopy structure tallied in a bibliographic search of the database BIOSIS (closed circles) and the total number of all citations indexed in BIOSIS for that year (× 10,000) (open circles). Note that the rate of publications concerning "canopy structure" greatly exceeds the rate of "all citations" after 1984, indicating the explosion of interest and study of forest canopy structure in recent years.

canopy researchers. Such "retrospective" use of data, however, requires the foresight to collect and record information that can act as a bridge to integrate separately collected data. Issues of how to organize these data so that researchers from varying specialities with unforeseen questions will become more significant. Thus, in the near future, canopy scientists will have to deal with new kinds of data, more data, and the need to share data.

The forest canopy is now recognized as a region of great ecological importance, but canopy studies are a relatively young and fragmented area of science. There have been no regular scientific meetings nor any scientific journal (although *Selbyana* has assumed this role) or professional society which focuses on canopy studies. To date, no one has worked out standardized, quantifiable, and cost-effective methods to characterize tree crowns and forest canopies. Little or no attention has been paid to problems of analyzing such data over time, which is necessary to use the extensive data available from sources such as NASA and Earth Observing System (EOS). With the increasing interest and amount of data on forest canopies, ecologists require the development of tools to manage and analyze their data and a means for comparing data from disparate studies.

In anticipation of these problems, an interdisciplinary group of forest canopy researchers, quantitative scientists, and computer scientists were motivated to establish the Canopy Research Network (CRN). Our goals are to develop methods to collect, store, display, analyze, and interpret three-dimensional (3-D) spatial data relating to tree crowns and forest canopies. In 1993, we received a planning grant from the Database Activities program of the National Science Foundation to: 1) compile an array of research questions and needs that involve canopy structure from the canopy research community; 2) examine potentially applicable information models and software tools that are in use in allied fields; and 3) develop conceptual models and recommendations for the types and format of information and analyses necessary to answer research questions posed by forest canopy researchers.

As a first step in this process, we broadly canvassed the diverse community of canopy scientists to understand: a) the characteristics, especially their questions, pathways of communication, and the scientific issues that are now understood to or might potentially require information on canopy structure; b) the specific attributes of canopy structure for which information is required, and c) existing useful manipulations and displays. A major emphasis is to discover if appropriate approaches and tools (e.g., software, statistical tests) for working with canopy structure already exist in other fields and need not be re-invented, i.e., might other fields that deal with 3-D tree-like data have come up with useful tools that could be modified and applied to true trees? This paper summarizes the results of a survey conducted to characterize the "state of the art" of canopy science, with particular emphasis on canopy structure. Details of the survey are available from the first author.

METHODS

A four-page survey was developed with input from forest ecologists, computer scientists, quantitative scientists, and a consulting sociologist. In October 1993, 428 surveys were sent to a mailing list compiled from four sources: 1) participants at recent canopy symposia; 2) authors of papers compiled from a computerized search of the literature on canopy structure (1980–current); 3) professional contacts from CRN participants; and 4) scientists who responded to our call for input in journals announcements, workshops, and professional meetings. A second mailing was sent two months after the first mailing to give all participants another chance to respond.

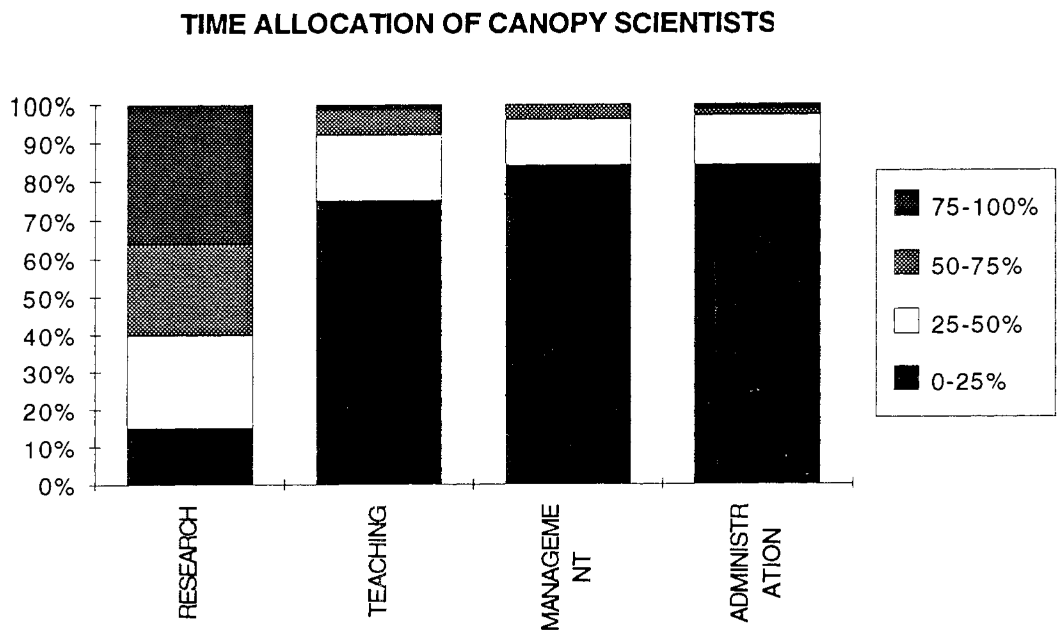

FIGURE 2. Time allocation of survey respondents. Canopy scientists were asked to report on the amount of time devoted to research, teaching, management, and adminstration.

RESULTS

A total of 220 (51%) surveys were completed and returned to us. These were tallied and entered into a database (Reflex2, Borland, Inc.) for analysis. A majority of surveys (ca. 65%) were returned within three weeks of the first mailing; ca. 15% after the second mailing, with the balance arriving over the ensuing three months. Supplementary information for some of the response was appended from comments received on the electronic mail bulletin board administered by the CRN (CANOPY@lternet.edu).

A. WHO ARE CANOPY SCIENTISTS?

We presented 13 choices of disciplines (including "other") for respondents to indicate their research and management interests. A total of 97% of the participants responded to this question, most with multiple descriptors (553 responses total). There were 10 categories with >15 responses: forest-atmosphere interactions (includes micrometeorology) (30% of total responses); tree architecture (13%); physiology (12%); arboreal animal ecology and plant/animal interactions (9%); epiphyte biology (8%); timber production (7%); taxonomy/systematics (6%); theoretical ecology (6%); ecosystem ecology (4%); and wildlife (3%). The category of "other research interests" (<2% each) included: biomechanics, canopy access, ethnobotany, hydrology, landscape and biosphere ecology, microbial ecology, pesticide management, remote sensing, modelling, mycology, phenology, and public education.

Respondents were asked to quantify the proportion of their time devoted to research, teaching, management and administration. Overall, a mean of 63% of their time was devoted to research, 25% to teaching, 21% to management and 19% to administration. FIG. 2 shows the distribution of their time in greater detail.

B. HOW DO CANOPY SCIENTISTS COMMUNICATE?

1. Journals. Respondents were asked to list the journals or newsletters they read for information on canopy research. A total of 170 (77%) listed at least one journal. Most respondents (84%) listed more than one, and 68% listed more than two. In the 473 responses, a total of 74 journals were cited. Nearly all of these were standard journals; only 2% of the responses cited a newsletter. Most were in general ecology journals (35%), with strong representation in other life science journals, including forestry (17%), botany (14%), tropical ecology (13%), and zoology (1%) journals. Only 13% were in what we categorized as "applied" journals. A substantial number of respondents listed journals in the physical sciences

TABLE 1. List of journals which respondents read for information on canopy research. Type indicates the area to which journal was classified (see text): app = applied; bot = botanical; bull = bulletin or newsletter; ecol = ecology; for = forestry; gen = general biology; geol = geology or geophysics; met = meteorology; rem = remote sensing; zool = zoology; trop = tropical. For frequency, *** indicates journal was cited more than 10%, ** indicates 5–10%, and * indicates 1–5%.

Journal name	Type	Frequency
Ecology	ecol	***
Agr. For. Met.	met, app	**
Biotropica	ecol, trop	**
J. Trop. Ecol.	trop, ecol	**
Can. J. For. Res	for	**
Bound. Layer Met.	met	*
Can. J. Bot.	bot	*
Current Contents	gen	*
Ecol. Applications	ecol, app	*
For. Ecol. Manage.	for, ecol	*
For. Sci.	for, app	*
Int. J. Rem. Sensing	rem	*
Oecologia	ecol	*
Tree Phys.	bot, for	*
Trees	bot, for	*
Oikos	ecol	*
J. Appl. Ecol.	ecol, app	*
J. Ecol.	ecol	*
J. Vege. Sci.	bot, ecol	*
Selbyana	bot	*
Rem. Sensing Env.	rem	*

Other journals (cited < 1% of responses) include: Acta Amazonica, Amer. J. Bot., Am. Nat., Am. Sci., Anim. Behav., Ann. Bot., Ann. Aci. For., Atm. Environ., Aust. J. Bot., Biogeochemistry, BioScience, Bryologist, Can. J. Rem. Sens., Cons. Biol., Ecol. Ent., Ecol. Modelling, Ecol. Monogr., Ekologia, Entomologist, Env. Exp. Bot., ESA Bull., Func. Ecol., Geophys. Letters, IEEE Trans. Geol., Int. J. Biomet., J. Anim. Ecol., J. Appl. Met., J. Env. Qual., J. Geology, J. Geophys. Res., J. Hydrol., J. Theoret. Biol., Lichenologist, Monthly Weather Res., Mycology, Mycotaxon, Operacion Canopee, OTS Liana, Photogramm. Eng., Plant Cell Env., Plant Soil, Polish Ecol. Studies, Q. J. Royal Met. Soc., Science, Tellus, Trans. Geosci. & Rem. Sens., Trends Ecol. Evol., Tropinet, Vegetatio, Water Air Soil Poll., W. J. App. For.

(17%), including meteorology (10%), remote sensing journals (5%), and geology (2%). Only a small proportion (3%) look to general science or biology publications. The list of journals cited is in TABLE 1.

2. Meetings. Respondents were asked to list the meetings they attend for information on canopy research. A total of 118 individuals (54%) attend at least one meeting per year. We categorized the 129 responses (17 different meetings, TABLE 2) into five categories: regular general ecology (47%), regular tropical biology (10%), regular physical science (14%), specialized canopy symposia (18%), and miscellaneous (11)%.

3. Electronic mail (e-mail) bulletin boards. Only 36 of the respondents (16%) currently subscribe to an e-mail bulletin board, but many more stated they anticipate access in the near future. Only 22% of those currently subscribed use more than one bulletin board. The greatest proportion of respondents (33%) who subscribe use ECOLOG, the electronic bulletin board of the Ecological Society of America. The rest of the bulletin boards had fewer than three subscribers (Table 3). There was strong interest (76%) in subscribing to the recently established canopy electronic mail bulletin board.

C. WHAT ARE THE METHODS AND TOOLS USED BY CANOPY SCIENTISTS?

1. Access. Nine methods of canopy access (including "other") were presented for respondents to describe as what they use (or have access) to gather data about tree crowns. The number of respondents to this question was 190 (86%), and the number of responses was 480. Most (73%) respondents use more than one type of access technique and 40% use more than two types of access techniques. The most frequently used methods are ground-based [(visual methods (24%) and remote sensing (15%)], followed by single tree-based [(ropes, (16%), portable scaffolding (14%), and spurs (5%)], with the fewest using permanent structures or machine-based access [(towers and masts (17%), cranes (4%), and hot-air balloons (3%)]. Other means of access used by respondents (<2% each) are: firearms, telescopic beams, traps winched into trees (e.g., litterfall and rain collectors), mathematical regressions, stem analysis, hydraulic lifts, free-climbing, tree bicycles, walkways, photography, LI-Cor LAI 2000 Takymeter, helicopter, pole pruners, video camera, and insecticidal fogging.

2. Software. We queried the respondents concerning their computer software and hardware in order to identify commonly used programs and to tailor future software programs to accommodate existing hardware capabilities. In the following section, we identify the most frequently used programs and list all programs cited by respondents in TABLE 3.

a. *Database programs:* A total of 183 respondents (67%) cited the use of database software, which included 29 programs. Two programs (Excel and Dbase) made up more than 60% of the usage. More than 70% of the programs are used by only one respondent.

TABLE 2. A list of meetings cited by respondents as being useful for exchange of canopy information. A total of 129 responses were tallied. Types are: a) regular general ecology (RGE); b) specialized canopy (SC); c) regular physical science (RPS); d) regular tropical ecology (RTE); and e) miscellaneous (MI). For frequency, *** indicates being cited >10%; ** indicates 5–10%; * indicates 1–5%.

Meeting	Type	Frequency
Ecol. Soc. Amer.	RGE	***
Assn. Tropical Biology	RTE	**
Other specialized canopy meetings	SC	**
Selby Gardens	SC	*
AIBS	RGE	*
Remote Sensing meetings	RPS	*
IUFRO Canopy Processes Workshop	SC	*
Amer. Meteorological Soc.	RPS	*
Agr. For. Meteorology	RPS	*
Mission Canopee	SC	*
IEEE	RPS	*
NW Lichen Guild	MIS	*
NW Science Meeting	SC	*

Other meetings (cited <1% of responses) include: Society for Cons. Biology, INTECOL, NASA, Botanical Soc. America.

b. *Statistical programs:* A total of 30 statistical packages were listed, most of which were cited by less than five respondents. Three packages are used by ca. 75% of the responses: SAS (36%), Systat (27%), and SPSS (11%).
c. *Graphics programs:* We asked respondents about software for graphics. A total of 123 people responded (56%), with 199 answers. A total of 36 programs are used by canopy researchers. Sigmaplot was the program most frequently cited (22%), and the most frequently program used alone. More than half (62%) use more than two programs for graphics needs.
d. *GIS programs:* One-third (68 individuals) of the participants responded to our query concerning GIS programs; 81 responses were recorded. Of these, most (88%) use four programs: ARC/INFO (52%), GRASS (15%), IDRISI (15%), and ERDAS (6%). The remaining 12% are used by only one or two individuals.
e. *Other software programs:* Eighteen other software systems were cited as being used by 36 canopy researchers. Seven stated they have developed their own programs using programming languages such as FORTRAN, C, and S.

3. Computer Hardware. Availability of computers is high among the respondents; 92% listed access to some type of computer. Over half of the participants (53%) have only a personal computer (PC) available. Of those that have PCs, more have access to IBM (79%) than MacIntoshes (Macs) (32%); 36% have access to the IBM only; 13% to a Mac only. Approximately 15% have access to both IBM and Macs. Of those with IBMs, most employ the 486 chip (69%); 5% have access only to the 286 chip. For Mac users, 40% have access to Mac II, 30% to the Quadra, 25% to a Powerbook, with the rest using SE, Classic, Centris, and other versions.

TABLE 3. Use of electronic mail bulletin boards by respondents. A total of 33 responses were tallied. For frequency, *** indicates being cited >10%; ** indicates 5–10%; * indicates 1–5%.

Email bulletin board path	Frequency
ECOLOG	***
Internet	**
Forest Service Econet	*
Taxacom	*
Entomol	*
Conslink	*

Other bulletin boards cited (<1% of responses) include: La Selva, Omnet, Scinet, Tropinet, Biodiversity, Climlist, FMDSS.

Workstations are available to 24% of the respondents. Most of these (60%) are SUN workstations. Others commonly used are Silicon Graphics (19%), DEC (7%), RISC (7%), HP (4%) and Digital (1%). Approximately 25% of respondents have both personal computers and workstations available; 3% have only workstations. Mainframe computers are less accessible to respondents than workstations and personal computers; only 27% of those responding use mainframes. Of the 57 responses, the most commonly used is a VAX (40%), followed by UNIX (30%), and IBM (23%). Others included DEC, HP, and Data General. Only 6% of the respondents have access to a supercomputer, which are split equally between Cray and Convex types. Only 3% have access to the full range of computer equipment (PC, mainframe, workstation, and supercomputer).

D. What are the primary issues and questions facing canopy scientists?

We received 180 responses (82%) describing primary issues and challenges facing canopy scientists. These encompass a range of issues including very general conceptual problems (e.g., development of sound statistical basis for 3-D data) and specific research questions (e.g., what is the sap volume of lianas?). We categorized the responses into similar categories to those of re-

TABLE 4. Software packages used by respondents. For frequency, *** indicates being cited >10%; ** indicates 5–10%; * indicates 1–5%. A. Database Packages, B. Statistical Packages, C. Graphics Packages, D. GIS Programs, E. Other software.

A. Database package	Frequency
Excel	***
Dbase	***
Lotus 1-2-3	**
Quattro Pro	**
Paradox	**
Access	*
INGRAss	*

Other database packages (cited <1% of responses) include: Oracle, 4th Dimension, ALPHA, Alpha 4, Cardbox, Codebase, Datachain, Filemaker Pro, Hypercard, INFO, Ingres, Knowledge Manager, Notebook, PC File, Q&A SPlus, Statgraphics, Statplan, Superbase, Sybase, Symphony, "my own."

B. Statistical package	Frequency
SAS	***
Systat	***
SPSS	***
Minitab	*
SPlus	*
Statgraphics	*
Statistica	*
Statistix	*
StatView	*
Statworks	*
Super Anova	*

Other statistics software (cited <1% of responses) include: Axum, Canaco, CoStat, Cricket, Excel, Genstat, GEO-EAS, Geostat, GLIM, GraphPad, Kwikstat, Mathematica, NCSS, NEVER, PCORD, Quattro Pro, S, Sigmastat, Statpak, Wavelet.

C. Graphics package	Frequency
Sigmaplot	***
Corel Draw	**
Cricket Graph	**
Deltagraph	**
Grapher	**
Sysgraph	**
Harvard Graphics	**
Axum	*
Canvas	*
Excel	*
Freelance	*
Kaleidagraph	*
Lotus 1-2-3	*
MacDraw	*
Paintbrush	*
PC Wave	*
Quattro Pro	*
SAS	*
SPlus	*
Statgraphics	*
Surfer	*

Other graphics software (cited <1% of responses) include: ALDUS, CoPlot, Down Point, DrawPerfect, Fullpaint, Genstat, Golden Software, Graph Pad, GraphTool, PCI, Power Point, SCI-GL, Statistica, WP Presentation, "Own Programs."

TABLE 4. Continued.

D. GIS package	Frequency
ARC/INFO	***
GRASS	***
IDRISI	***
ERDAS	**

Other GIS programs (cited <1% of responses) include: KWIS, PCI, Intergraph MGE, SPLUS, Delta Data Systems, Autocad, ATLAS-GID, PMAP, Roots-Pro.

E. Other software program	Frequency
"My own"	***
FORTRAN	**
C	*
Image analysis software	*
Quattro Pro	*

Other software (cited <1% of responses) include: Asterix, Canoco, Eco-aid, Gauges, Geo-EAS, Hypercard, Lotus 1-2-3, Microstat, Mocha Image Analysis (Jandel), Phytotab, Pro-Cite, (Bibliographic Software), Quick BASIC, Silvistar, Stella, VESPAN, Voyager, Word, Wordstar 7.

search interests (A.1, above). In some cases, we combined responses that were identical or nearly identical but tallied the number of responses separately. The most commonly cited issues were in the areas of forest-atmospheric interactions (26%) and tree architecture (23%). Fewer questions involved biotic questions: arboreal animal ecology (12%), epiphyte ecology (9%), ecosystem ecology (9%) and physiology (9%) concerning plant and animal distribution (Table 5). Remote sensing questions made up 8% of the responses. Few questions related to timber production (2%), general theoretical areas (1%), and canopy access (1%). We present the list of questions posed in Appendix 1.

E. WHAT ARE THE OBSTACLES FACING CANOPY SCIENCE?

We presented four general potential obstacles to canopy structure research to the respondents, and asked them to rank them from being very important (1) to not at all important (5). The four obstacles listed were: a) difficulty of physical access to the canopy; b) lack of a body of long-term background data collected with standard techniques; c) difficulty with portraying 3-D data on 2-D planes, and d) lack of statistical packages that deal with 3-D data.

The first two issues (difficulty access and lack of data) were perceived as being more problem-

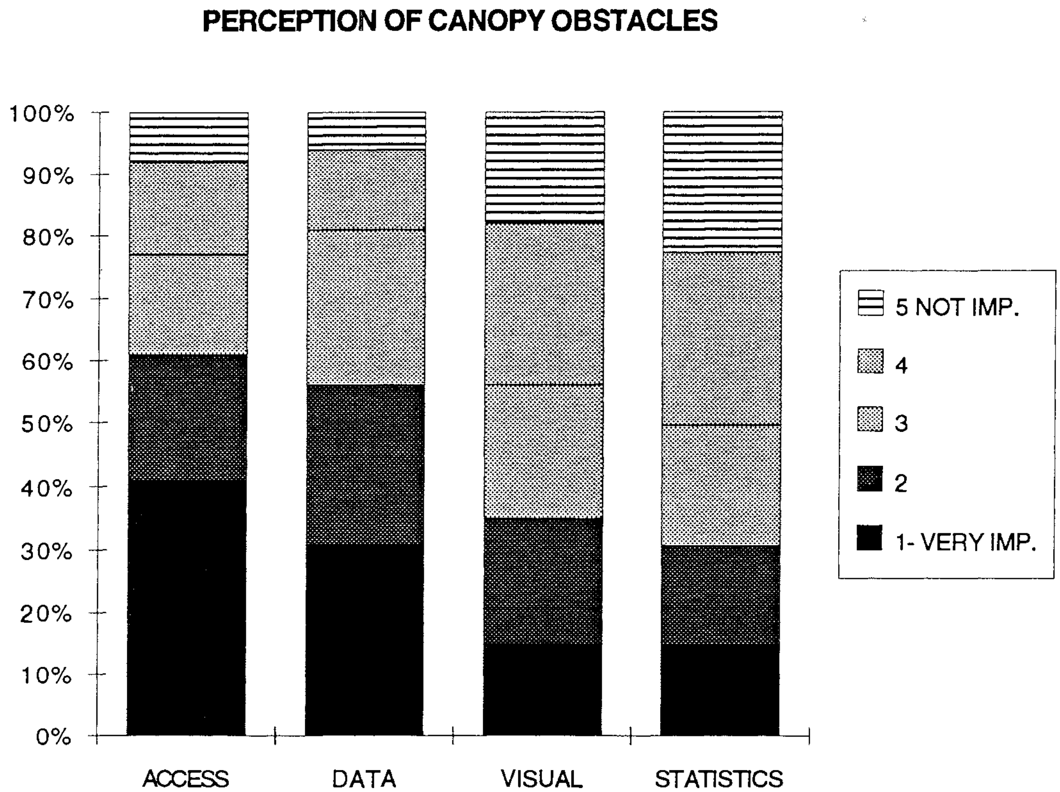

FIGURE 3. Perception of obstacles to advancing canopy science. Respondents to survey rated four possible types of obstacles as very important (1) to not important (5). Obstacle types are: a) difficulty of physical access to canopy ("access"), b) lack of long-term background data collected with standard techniques ("data"), c) difficulty with visually portraying 3-D data on 2-D planes ("visual"), and lack of statistical packages that deal with 3-D data ("statistics").

atic than the second two (difficulty of portraying 3-D data and lack of statistics packages). For access, 61% rated the obstacle as very important (rated as 1 or 2), and only 23% rated it as not important (4 or 5). For lack of a body of standardized data, 56% rated it as very important, and 19% as not important. In contrast, 34% of respondents rated visualization of 3-D data as important, and 44% as not important. Lack of statistical packages was deemed important by only 31% of the respondents and not important by 51% (FIG. 3).

Other obstacles were described by 35 respondents (44 responses). These were allocated to six categories: logistics and lack of funding (32%), lack of data (23%), difficulties of access and sampling (18%), problems with data management (11%), lack of cross-disciplinary cooperation and communication (9%), and conceptual problems (7%). Detailed descriptions of perceived obstacles are in Appendix 2.

F. WHAT CONCEPTUAL MODELS AND TOOLS MIGHT BE USED TO OVERCOME THESE OBSTACLES?

Fifty-two respondents suggested conceptual models, analytical developments, or resources which they feel hold promise in addressing the problems facing canopy research. We grouped these suggestions into six categories: mathematical approaches (including statistics, modelling, and fractals) (34%); software programs (including image analysis and GIS approaches) (23%); instrumentation (12%); access (11%); tree architecture and physiology (11%); and remote sensing (9%). Details are in Appendix 7.

DISCUSSION

The portrait of canopy science and canopy scientists emerges from this survey as complex and extremely multifaceted. We found the young field of canopy science to be fragmented, with a tremendous range of questions spanning wide spatial scales and approaches. Canopy scientists have a wide range of tools available, both for access and data analysis, but few avenues for formal communication and synthesis among disciplines. Interests, backgrounds, perceived problems and ways of overcoming them are as broadly scattered as the roster of an entire university. Qualitative and quantitative approaches are used; descriptive, experimental, and modelling studies have a place in understanding the canopy.

Tools currently used by canopy scientists range from the very simple to the highly technical. Canopy science is no longer the realm of the mountain-climber or hot-air balloonist; many in this field appear to be strongly grounded in highly technical instrumentation and many have access to workstations, supercomputers, and sophisticated software and data analysis. We were surprised that access to the canopy persists in being perceived as a major obstacle to understanding canopy processes. Given the recent major strides in canopy access techniques, we had anticipated that access would rank lower in importance compared to data management and analysis.

There was a strong "sense" for the need to exchange information and tools between biotic and abiotic studies. Many of the primary issues described by respondents interested in primarily ecological or physiological questions will require an understanding (or at least data) on structural and physical aspects of the canopy. Conversely, those from remote sensing backgrounds showed strong interest in validation of their ability to portray forest canopies and wished to seek the biological or physiological "meaning" for their images.

Very little comparative work using comparable measurements between different forest types has been done. One limitation to accurate comparative work is the absence of standard protocols. The large number of disparate pathways of communication revealed in this survey (meetings, journals, electronic mail bulletin boards) is a key to why comparative canopy work is rare. There is no single journal or meeting where these disparate disciplines can come to gather easily.

In summary, the field of canopy science is growing in importance, size, and diversity. Canopy science is being approached in multifaceted ways by scientists with a tremendous diversity of skills, instruments, and expertise. However, the tools to answer the questions of greatest interest are not yet readily or equally available to canopy scientists. To solve the complex questions the canopy presents, we will need not only more sophisticated techniques of access, statistics, graphics, and data management, but also a network of communication and cooperation to exchange ideas and information.

Acknowledgments

David Ford and Judy Cushing contributed to the concepts and ideas behind the Canopy Research Network and the survey. Cara Stallman provided excellent logistical help with administering the survey. Thanks to Laura Schrager for help with the survey. Support was from a planning grant from the Database Activities Program (Division of Instrumentation and Resources) of the National Science Foundation (BIR 93-07771), a grant from the Ecosystems Program of the National Science Foundation (BSR 90-18006), and a Faculty Sponsored Research grant from The Evergreen State College.

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Appendix 1

Primary issues and questions which respondents feel require information on canopy structure, grouped by category of canopy research and management interest in table interest. Only those not previously mentioned or summarized in the text are presented. Numbers in brackets indicate number of respondents with identical or nearly identical responses.

Canopy access

Developing techniques of canopy access

How do we measure, quantify, describe, and illustrate canopy structure for utility of a broad group of researchers?

Arboreal animal ecology

How are ground and canopy organisms related trophically? Where are organisms living in the canopy?
What are the abundances, distributions, and consequences of plant-arthropod mutualisms?
Does the position of the reproductive organs of plants influence the kind of vectors, pollinators or dispersing them?
How does canopy structure influence vertebrate assemblages, especially pollinators and dispersers?
What is the relationship between leaf arrangement and density, floral presentation, and pollinator species behavior and color sensitivity?
Quality and quantity of the sunflecks that serve as main habitat of Odonota for sexually immature stages.
Insect biodiversity, density, movements, distribution, and ecology, especially trophic relationships (6).
What is the composition of free-feeding Lepidoptera in the canopy and that of the insect parasitoids that attack them?
How might canopy removal in an agricultural setting (e.g., shade trees in a coffee plantation) affect the diversity of ground-dwelling invertebrates?
Canopy distribution of tardigrades, protozoans, pterygote insects, and nematodes in relation to microclimate and vegetation structure? (3).
What is the quantity of arthropods in the canopy that serve as food for insectivorous birds? How does fragmentation of the forest canopy affect arthropod diversity?
The flowering and fruiting phenologies of canopy trees and populations of pollinators and frugivores; keystone resources.
Patterns of vertical distribution of small mammals in tropical canopies: a) Why do some mammals prefer only higher or medium strata? b) What is the difference in resource availability in the floor and in the different forest strata?
Birds and mammal use of the forest canopy, especially locomotion.
Impact of introduced mammals on indigenous canopies.
How do changes in canopy structure resulting from forest disturbance, degradation or restoration, affect arboreal bird species?

Ecosystem ecology

Estimation of total canopy biomass, surface area, and nutrient pools, including leaves, twigs, branches and woody boles (4).
Use of leaf surface area to estimate canopy nutrient fluxes.
Relationship between canopy structure and community biodiversity, water use, and nutrient fluxes (2).
Structural diversity as it varies across the landscape & with seral stages.
Volume of standing dead biomass in canopy as source of nutrients and woody debris.
Canopy dynamics and litterfall in forest plantations.
How is canopy structure affected by treefalls? How are treefall gaps filled in (canopy development)? How does canopy structure affect the light availability at the forest floor (2)?
Canopy decline or dieback is a widely observed phenomenon in some forests. How are natural (i.e., life-stage associated) declines distinguished from those which are human-induced or pathological?
Leaf phenology, growth dynamics, and herbivory in cloud forest trees.
What is the relationship between natural regeneration and overstory canopy structure in old-growth forests?
How do site factors affect forest canopies?
How do forest canopies respond to different types of disturbances and forest stresses (e.g., drought, soil acidification, air pollution (3)?
Ecosystem response to global warming.

Epiphyte ecology

Are there epiphytes coevolved with host species? Which species of epiphytes are obligatory on its host species?
What are the cryptogamic components of canopies? How does epiphyte biomass and composition depend on forest dynamics, structural diversity, historical carryover on canopy components from previous cohorts?
Succulent epiphytes
How does the chemistry in substrates differ within and among tree crowns and how may it affect epiphyte success?
How are various groups of epiphytes (e.g. Cyanolichens) distributed throughout tree crowns? What are the habitat requirements of individual epiphyte species, especially those restricted to or associated with old-growth forests?
Gene flow in and among populations of epiphytes; microsite limitations to life history and distribution of epiphytes.
What are the determinants of canopy structure for microhabitat for epiphytes?
What is the 3-D arrangement of plant diversity in tropical rain forest?
How does canopy architecture interact with epiphyte species diversity and composition (3)?

What is the dynamics of the canopy (e.g. expansion rate, branch fall, age of individual branches) in relation to the dynamics of epiphyte succession, colonization rate, and mortality?

Assess and describe epiphyte densities for demographic studies.

The effects of the epiphyte community on nutrient cycling.

Diversity and role of fungal decomposers in epiphyte communities.

The influence of canopy processes on mistletoe population dynamics.

Sizes, inclinations, and spatial arrangements of branches, lianas, and hemiepiphytes.

How does canopy structure relate to hemiepiphyte establishment and growth, and host selectivity by hemiepiphytes?

Ecophysiology (e.g., sap fluxes) of lianas.

FOREST-ATMOSPHERE INTERACTIONS (including microclimatology and light)

What is the Leaf Area Index of a forest and of canopy components (14)?

How does competition for light influence tree species composition? What are the differences in forest atmosphere interaction between heterogeneous multi-species canopies and idealized "big leaf" canopies?

Light interception and penetration; amount and display of evaporative surface area (7).

Absorption of PAR by tree canopies, and its relationship to LAI.

Influence of changing canopy structure with the invasion of alien trees on understory light availability and resulting effects on regeneration and growth of native and alien species.

Carbon and water exchange of whole canopies with the atmosphere.

Does advection of sensible heat from forest clearings accelerate transpiration from adjacent intact forest? How deeply does the effect penetrate into the intact forest? To what degree is increased transpiration attributable to increased insolation rather than advection?

Atmospheric deposition modeling.

How are photosynthetic enzymes and nitrogen distributed in the canopy (mass and position) in foliage and branches?

How should the canopy be described in terms of its aerodynamic drag? How do individual leaves, branches, and clusters interact with, and create turbulence in the flow field?

Application of canopy resistance models for air/surface exchange.

How do we describe the surface roughness of a canopy, and how does the degree of roughness affect the coupling of forest to atmosphere for water and heat exchange?

Wetting up response of canopies, drop size modification, cloud deposition, rainfall interception, and aerodynamic deposition.

Research on the mechanics of aerosols as related to terrestrial and aquatic systems needs information on: 1) leaf/needle geometry and dimensions (possibly fractal dimensions); 2) whole-tree structure; 3) stand structure and architecture.

What is the spatial distribution of canopy elements that may serve as: 1) drag surfaces; 2) low-pan filters for turbulence; 3) absorbers, reflectors, or transmitters of radiation; 4) sinks of CO2, water vapor, pollutant gases and particles? Can forest environments be predicted from an understanding of canopy structure?

The effects of hurricanes on the structure, regeneration and success of forests.

How does branch angle and structure affect precipitation flow volume and chemistry?

Phenological changes in the canopy with varied light and rainfall regimes.

Forest-atmosphere interaction for use in meteorological weather, prediction models (Hirlam model).

Micro-meteorology of tropical rainforest canopies in relation to diurnal and seasonal changes weather conditions. Radiation exchange above and within tropical forest canopies- effect of changes in forest phenology and sun-earth geometry.

Trace gas emissions and deposition of reduced sulfur compounds, hydrocarbons, and ammonia (2).

What are the canopy element distributions that affect the transport of gases and aerosols in vegetation?

Where does nitrogen fixation occur in the canopy? How does the canopy intercept wet and dry deposition?

How does canopy structure and metabolism influence the behavior of ozone (2)?

Aerosol and pollutant deposition on the different types of forests in industrialized regions (3).

Measurement and modeling of canopy uptake of atmospheric pollutants.

PHYSIOLOGICAL PROCESSES

What proximal and ultimate factors limit floral production and seed maturation?

Regulation of water vapor and CO_2 fluxes from leaf to canopy.

What is the distribution of leaf area for purposes of evaporation model, radiation transfer modeling, and scaling stomatal conductance?

Carbon/water balances, NPP, foliage chemistry (2).

How do alterations in cuticle physiochemical characteristics affect canopy/atmosphere exchange?

Canopy photosynthesis, transpiration, radiation absorption (5).

What is the photosynthetic contribution of different portions of the canopy to whole-point carbon assimilation?

How do plants intercept light?

How is branch growth controlled?

LAI and leaf only distribution to calculate radiation absorption with a multilayer model.

Distribution of leaf area in canopy for modeling water use and dry matter production.

What is the leaf longevity and phenology of the canopy? How does leaf phenology affect canopy architecture? How does canopy architecture affect photosynthesis of individual leaves?

Remote sensing

What is the physiological meaning of remote sensing images of trees?

Development of remote sensing techniques to understand canopy structure (7).

Can physiological &/or physical attributes of canopies be determined from arboreal-canopy spatial observations? What are the relationships between spatial information obtained from satellites and canopy attributes, with the goal of global monitoring methods?

Remote sensing of vegetation biomass using radar sensors requires extensive knowledge of individual and stand architecture, geometries, and density.

Satellite access to representative areas of canopy.

Field determination, modeling and development of relationships between architecture and remotely sensed measurements.

Model forest canopies radiometric patterns viewed from an airborne or space platform to study light regimes and tree architecture.

Tree structure (geometry) for radar modeling.

Tree architecture

Object oriented modeling of tree crowns.

To what extent can plant functional attributes be used as surrogates to indicate plant/environment interaction?

Modeling tree crown form & branching models.

Timber production

Effects of different logging intensities on botanical species and ecosystem diversity.

Tree crowns as hazards to humans: architecture, vitality, and deterioration ratios.

Canopy chemistry in relation to root rot.

Alterations to canopy structure and composition by selective logging.

What crown features are used to select trees for retention at the time of harvest? How does the tree respond by species, site, crown class) to retention or removal? How can silviculture advance the method of growth based on canopy control?

How does stand structural diversity vary with stand age and type? How do silvicultural treatments affect wildlife habitat and timber production? Where is leaf area in canopy space change through succession, and how does this affect wildlife?

Foliar surface area vs. canopy volume and forest floor area in deciduous vs. coniferous trees.

What is the relationship between the individuals forming the tree, seen itself as a colony?

Crown shape, volume, leaf area; how they influence tree growth and tree uses (e.g., wood quality, wildlife).

How important is strata/canopy overlap in determining community composition?

Distribution of foliage and other canopy elements within crowns of individual trees and stands (7).

Prediction of crown length and change in crown length, crown width and change in crown shape, branch lengths, branch diameter, branch angles, and number of branches per whorl.

What is the relationship between crown structure and tree biomechanics?

What are useful methods and parameters to characterize the internal space of forest stands?

What is the canopy architecture in relation to: 1) amount of leaf area, biomass, and physiological activity of assimilatory apparatus; 2) stemwood production; and 3) solar radiation and air pollution?

How does crown shape change with advancing tree age and relative canopy position (e.g., from an intermediate to dominant crown class)?

How does the structure of the canopy affect the leaf environment? How does one scale leaf-level processes to the whole canopy (3)?

Distribution of leaf area, physiological characteristics of leaves from different canopy areas, distribution and among of foliage consumption areas, refoliation and dieback patterns of the canopy (3).

Develop an efficient method to describe 3-D canopy structure.

Distribution of foliar mass by foliar age, class, temperatures, wind speed, etc.

To what extent are individual tree canopies interconnected?

Number, diameter, length, and angular distribution of branch segments and leaves as inputs to model of radar backscattering from forests.

Relations between species diversity and canopy structure.

Spatial variability of canopy tree architecture; Pielectric constants of components, spectral characteristics of components, and diffusion properties of canopy materials at visible and microwave wavelengths.

What is the relation between tree architecture and forest architecture?

What are the phenomena responsible for tree crown shapes? Is there a general rule in self-pruning of branches and how is this phenomenon affected by environmental conditions?

Appendix 2

Issues and questions which respondents feel present obstacles to their work on forest canopy structure. Only those not previously mentioned or summarized in the text are presented. Numbers in brackets indicate number of respondents with identical or nearly identical responses.

Lack of concepts

Difficulty in knowing what information is really needed.

Lack of knowledge of what is possible to study, given present systems.

Lack of a conceptual models of canopy structure that are clearly linked to significant canopy functions, identification of a minimal set of canopy attributes of broad interest that can be measureed easily and used to explain important functions.

Lack of data

Lack of insect systematists for identification of canopy insects.

Availability of allometry for above ground biomass; lack of good measurement devices for height, LAI, and canopy closure.

Lack of simulation models for forest-atmosphere interactions in 3-D; lack of landscape-level data.

Lack of inventories.

Lack of research in the field of tree crown illumination

Micrometerorologists studying forest atmosphere coupling tend to shy away from forest edges because eddy correlation techniques require uniform mixing.

Conversion factors between historic data (e.g., crown size) to biophysical parameters.

From a modeling perspective there is very little data on LAI, canopy roughness, albedo, atmosphere coupling with stomata, etc.

Fast and high accuracy of structure induced turbulence, and of pH-gradients close to surfaces.

Lack of precise knowledge of growth and branching patterns in trees. Poor knowledge of the relations betweenwidth and growth and architectural development.

Problems with data management

Difficulty in database management. There is not a database system to deal with host species, epiphyte species, epiphytes collected, and sample plots.

It is very difficult to visualize 3-D density distribution.

Analytical obstacle with engineering data.

Lack of convenient time-series software.

Analysis of photographic and light transmittance data in 3-D.

Lack of cooperation and communication

Need a network to look at factors that shape arboreal communities across a wide geographic range.

Lack of standardized measures of crown/canopy parameters.

Lack of standard ways of simulating biologically realistic forest canopy structures and their changes over time.

Difficult to collaborate with scientists on large-scale projects.

Cooperation between different disciplines

Difficulty with access and sampling

Access and sampling in a 3-D canopy (3).

Physical access and observing canopy animals, many of which are nocturnal.

Lack of a rigorous, yet easy to use structural description of tree geometry and canopy geometry, such that one can do unbiased sampling or summarize positions in a canopy.

High-quality aerial stereogrammetry.

Securing samples from the mid to upper parts of the crown in a cost-effective manner.

Access and sampling in a 3-D canopy (3)

The very large variation in rainfall extent type and amount type; duration,intensity, rain angle, and wind speed and direction.

Difficulty of sampling variability over a stand (or landscape of stands. Towers can reach only limited numbers of trees).

Adverse climatic conditions, particularly wind affect our sampling efficiency.

Lack of funding and logistical problems

Funding (8)

We now use a crane so the difficulty is cost instead of access.

Availability of LONG-term funding that will reveal true patterns as opposed to glimpses.

Lack of field time.