Smithsonian UNEP GCP Global Canopy Programme

Studying Forest Canopies from Above: The International Canopy Crane Network

Edited by Yves Basset, Vibeke Horlyck & S. Joseph Wright

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The International Canopy Crane Network

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Smithsonian Tropical Research Institute (Panama)
With the generous help of the United Nations Environmental Programme (UNEP)

Smithsonian UNEP GCP Global Canopy Programme

Published by the Smithsonian Tropical Research Institute, Panama
and the United Nations Environmental Programme

Smithsonian Tropical Research Institute
Apartado 2072
Balboa, Ancon
Republic of Panama

Studying Forest Canopies from Above: The International Canopy Crane Network
Edited by Yves Basset, Vibeke Horlyck & S. Joseph Wright
ISBN 9962-614-05-8

Printed in Bogota, Colombia, by Editorial Panamericana de Colombia
Calle 65 No. 95-28, Bogotá, Colombia. Web: www.panamericanafei.com

Designed by Hanly Design, Panama. Email: hanlydes@cableonda.net

Cover photographs: The San Lorenzo Canopy Crane in Panama, viewed from the arm. Inset: entomologists collecting insects visiting flowers in the canopy of San Lorenzo (photographs Marcos Guerra).

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CONTRIBUTORS

Dieter Anhuf
Instituto de Estudos Avancados da Universidade de São Paulo, Av. Prof. Luciano Gualberto Travessa J, 374 05508-900 São Paulo, Brazil. Email: anhuf@usp.br

Héctor Barrios
Programa de Maestría en Entomología, Universidad de Panamá, Panamá City, Republic of Panamá. E-mail: hbarrios@ancon.up.ac.pa

Yves Basset
Smithsonian Tropical Research Institute, Apartado 2072, Balboa, Ancon, Panama City, Republic of Panama. E-mail: bassety@tivoli.si.edu

Ariadna Bethancourt
Universidad de Panamá, Panamá City, Republic of Panamá.

Ken Bible
Wind River Canopy Crane Research Facility, University of Washington, 1262 Hemlock Road, Carson, WA 98610, USA. E-mail: kbible@u.washington.edu

Stephanie A. Bohlman
College of Forest Resources, University of Washington, Seattle, WA 98195, USA. E-mail: bohlman@u.washington.edu

Michael Bredemeier
Forest Ecosystems Research Center, University of Göttingen, Buesgenweg 2, D-37077 Göttingen, Germany. E-mail: mbredem@gwdg.de

Michael Cermak
James Cook University, Cairns Campus, PO Box 6811, Cairns Qld 4870, Australia.
E-mail: Michael.Cermak@jcu.edu.au

Pierre Charles-Dominique
Museum National d'Histoire Naturelle, Avenue du Petit Château 4, 91800 Brunoy, France. E-mail: Pierre.Charles-Dominique@wanadoo.fr

Lucy Chong
Forest Research Center, Forest Department Sarawak, Kuching, Sarawak, Malaysia. E-mail: chongl@tm.net.my

Achim Dohrenbusch
Institute for Silviculture, University of Göttingen, Buesgenweg 2, D-37077 Göttingen, Germany. E-mail: adohren@gwdg.de

Peter Fabian
Bioclimatology and Pollution Research, Center of Life Sciences Weihenstephan / Technische Universität München, D - 85350 Freising, Germany. E-mail: fabian@met.forst.tu-muenchen.de

Martin Freiberg
Abteilung Systematische Botanik und Ökologie, Universität Ulm, Albert-Einstein-Allee 11, D-89081 Ulm, Germany. E-mail: martin.freiberg@biologie.uni-ulm.de

Gregory S. Gilbert
Environmental Studies, University of California, 1156 High St., Santa Cruz, CA 95064, USA. E-mail: ggilbert@ucsc.edu

Guillermo Goldstein
Department of Biology, University of Miami, Coral Gables, FL 33124, USA. E-mail: goldstein@bio.miami.edu

Martin Gossner
Land Use Planning and Nature Conservation, Center of Life Sciences Weihenstephan / Technische Universität München, D - 85350 Freising, Germany. E-mail: martin.gossner@lrz.tum.de

Gerhard Gottsberger
Abteilung Systematische Botanik und Ökologie, Universität Ulm, Albert-Einstein-Allee 11, D-89081 Ulm, Germany. E-mail: gerhard.gottsberger@biologie.uni-ulm.de

Eric A. Graham
Centro de Investigación Científica de Yucatán, Unidad de Recursos Naturales, Calle 43 #130, Col. Chuburná de Hidalgo 97200, Mérida, Yucatán, México. E-mail: graham@cicy.mx

Axel Gruppe
Animal Ecology, Center of Life Sciences Weihenstephan / Technische Universität München, D - 85350 Freising, Germany. E-mail: gruppe@zoo.forst.tu-muenchen.de

Karl-Heinz Häberle
Ecophysiology of Plants, Center of Life Sciences Weihenstephan / Technische Universität München, D - 85350 Freising, Germany. E-mail: haeberle@wzw.tum.de

Christian Heerdt
Bioclimatology and Pollution Research, Center of Life Sciences Weihenstephan / Technische Universität München, D - 85350 Freising, Germany. E-mail: heerdt@met.forst.tu-muenchen.de

Tsutom Hiura
Tomakomai Experimental Forest, Tomakomai Research Station, Hokkaido University Forests, Takaoka, Tomakomai, 053-0035, Japan. E-mail: hiura@exfor.agr.hokudai.ac.jp

Peter J. Horchler
Institut für Botanik, Spezielle Botanik & Botanischer Garten, Universität Leipzig, Johannisallee 21-23, D-04103 Leipzig, Germany. E-mail: horchler@uni-leipzig.de

Vibeke Horlyck
Smithsonian Tropical Research Institute, Apartado 2072, Balboa, Ancon, Panama City, Republic of Panama. Now at: Centre Thématique Européen pour la Conservation de la Nature, Museum National d'Histoire Naturelle, 57 rue Cuvier, 75231 Paris Cedex 05, France. E-mail horlyck@email.dk

Kaoru Kitajima
University of Florida, Department of Botany, 220 Bartram Hall, Gainesville, FL 32611-8526, USA. E-mail: kitajima@botany.ufl.edu

Christian Körner
Botanisches Institut der Universität Basel, Schönbeinstrasse 6, 4056 Basel, Switzerland. E-mail: Ch.Koerner@unibas.ch

Manuel T. Lerdau
Ecology and Evolution Department, State University of New York, Stony Brook, NY 11794-5245, USA. E-mail: manuel.lerdau@sunysb.edu

Michael Leuchner
Bioclimatology and Pollution Research, Center of Life Sciences Weihenstephan / Technische Universität München, D - 85350 Freising, Germany. E-mail: leuchner@met.forst.tu-muenchen.de

Christian Listabarth
Konrad Lorenz-Institut für Vergleichende Verhaltensforschung der Österreichischen Akademie der Wissenschaften, Savoyenstrasse 1a, A-1160 Wien, Austria. E-mail: c.listabarth@klivv.oeaw.ac.at

Rainer Matyssek
Ecophysiology of Plants, Center of Life Sciences Weihenstephan / Technische Universität München, D - 85350 Freising, Germany. E-mail: matyssek@wzw.tum.de

Frederick C. Meinzer
USDA Forest Service, Forestry Sciences Laboratory, 3200 SW Jefferson Way, Corvallis, OR 97331, USA. E-mail: Rick.Meinzer@orst.edu

Andrew W. Mitchell
Global Canopy Programme, Halifax House, University of Oxford, 6-8 South Parks Road, Oxford OX1 3UB, United Kingdom. E-mail: a.mitchell@globalcanopy.org

Wilfried Morawetz
Institut für Botanik, Spezielle Botanik & Botanischer Garten, Universität Leipzig, Johannisallee 21-23, D-04103 Leipzig, Germany. E-mail: morawetz@uni-leipzig.de

Masashi Murakami
Tomakomai Experimental Forest, Tomakomai Research Station, Hokkaido University Forests, Takaoka, Tomakomai, 053-0035, Japan. E-mail: masa@exfor.agr.hokudai.ac.jp

Nalini Nadkarni
The Evergreen State College, Olympia, WA 98505, USA. E-mail: NadkarnN@evergreen.edu

Tohru Nakashizuka
Research Institute for Humanity and Nature, Kamigyo, Kyoto 602-0878, Japan. E-mail: toron@cikyu.ac.jp

Angela J. Nunn
Ecophysiology of Plants, Center of Life Sciences Weihenstephan / Technische Universität München, D - 85350 Freising, Germany. E-mail: nunn@wzw.tum.de

Frode Ødegaard
Norwegian Institute for Nature Research (NINA), Tungasletta 2, NO-7485 Trondheim, Norway. E-mail: frode.odegaard@nina.no

Geoffrey G. Parker
Smithsonian Environmental Research Center, 647 Contee's Wharf Road, Edgewater, MD 21037, USA. E-mail: parkerg@si.edu

Ilja M. Reiter
Ecophysiology of Plants, Center of Life Sciences Weihenstephan / Technische Universität München, D - 85350 Freising, Germany. E-mail: reiter@wzw.tum.de

Don R. Reynolds
Botanical Studies Division, Natural History Museum, 900 Exposition Boulevard, Los Angeles, California 90007, USA. E-mail: dreynold@nhm.org

David W. Roubik
Smithsonian Tropical Research Institute, Apartado 2072, Balboa, Ancon, Panama City, Republic of Panama. E-mail: roubikd@tivoli.si.edu

Shoko Sakai
University of Tsukuba, Institute of Biological Sciences, Tsukuba, Ibaraki, 305-8572, Japan. E-mail shoko@biol.tsukuba.ac.jp

Mirna Samaniego
Smithsonian Tropical Research Institute, Apartado 2072, Balboa, Ancon, Panama City, Republic of Panama. E-mail: SamanieM@tivoli.si.edu

David C. Shaw
University of Washington, 1262 Hemlock Road, Carson, WA 98610, USA. E-mail: dshaw@u.washington.edu

Ulrich Simon
Land Use Planning and Nature Conservation, Center of Life Sciences Weihenstephan / Technische Universität München, D - 85350 Freising, Germany. E-mail: sim@lwf.uni-muenchen.de

Jed P. Sparks
Department of Ecology and Evolutionary Biology, Cornell University, Ithaca, NY 14853, USA. E-mail: jps66@cornell.edu

Albert-Dieter Stevens
Abteilung Systematische Botanik und Ökologie, Universität Ulm, Albert-Einstein-Allee 11, D-89081 Ulm, Germany. E-mail: albert-dieter.stevens@biologie.uni-ulm.de

Nigel E. Stork
Australian Canopy Crane Pty Ltd and Cooperative Research Centre for Tropical Rainforest Ecology and Management, James Cook University, Cairns Campus, PO Box 6811, Cairns Qld 4870, Australia. E-mail: nigel.stork@jcu.edu.au

Sunshine Van Bael
Smithsonian Tropical Research Institute, Apartado 2072, Balboa, Ancon, Panama City, Republic of Panama. E-mail: vanbaels@si.edu

Herbert Werner
Bioclimatology and Pollution Research, Center of Life Sciences Weihenstephan / Technische Universität München, D - 85350 Freising, Germany. E-mail: werner@met.forst.tu-muenchen.de

Jens Wesenberg
Universität Leipzig, Institut für Botanik, Spezielle Botanik, Johannisallee 21-23, D-04103 Leipzig, Germany. E-mail: wesenb@uni-leipzig.de

Gustav A. Wiedey
Forest Ecosystems Research Center, University of Göttingen, Buesgenweg 2, D-37077 Göttingen, Germany. E-mail: gwiedey@gwdg.de

Hans Winkler
Konrad Lorenz-Institut für Vergleichende Verhaltensforschung der Österreichischen Akademie der Wissenschaften, Savoyenstrasse 1a, A-1160 Wien, Austria. E-mail H.Winkler@klivv.oeaw.ac.at

Klaus Winter
Smithsonian Tropical Research Institute, Apartado 2072, Balboa, Ancon, Panama City, Republic of Panama. E-mail: winterk@tivoli.si.edu

S. Joseph Wright
Smithsonian Tropical Research Institute, Apartado 2072, Balboa, Ancon, Panama City, Republic of Panama. E-mail: wrightj@tivoli.si.edu

Gerhard Zotz
Botanisches Institut der Universität Basel, Schönbeinstrasse 6, 4056 Basel, Switzerland. E-mail: gerhard.zotz@unibas.ch

FOREWORD

Despite rapid technological advances during the 20th and 21st centuries, in areas such as space exploration, information networks and molecular biology, mankind is far from having understood the complex web of life on Earth. This is evidenced by global environmental problems, such as climate change and loss of biodiversity, to which UNEP has responded by supporting multilateral environmental agreements, making information available for decision-making, and also strengthening the scientific basis for policy. Lack of baseline knowledge about biotic interactions is nowhere more acute than in habitats difficult to access, such as forest canopies, particularly tropical forest canopies. These habitats are among the richest and most threatened on Earth, yet so little is known about them. As they quickly disappear, a wealth of genetic information is becoming extinct before mankind can access it and assess how it could be put to use to improve the lives of present and future generations.

Hence, UNEP is working closely with different centers of excellence to explore and assess the influence that forests have on both regional and global climates. UNEP has emphasized that research should be promoted at the interface between forest components, and the atmosphere and in forest canopies to study the effects of climate change and biodiversity, respectively (CBD, COP 6/20). To this end, two canopy access facilities were funded in Panama by the generous support of the Smithsonian Institution and its National Board of Associates and by the governments of Belgium, Denmark, Finland, Germany and Norway through the clearinghouse mechanism of UNEP. The UNEP project *Assessment of Biological Diversity and Microclimate of the Tropical Forest Canopy* attracted considerable interest from scientists and was instrumental in generating an array of studies published in leading scientific journals.

This example was followed by others and resulted in the creation in 1997 of the International Canopy Crane Network (ICCN), which currently includes 11 crane facilities, located in widely different forest types in four tropical and four temperate countries. The network is dedicated to study key canopy processes at the local and regional levels, such as the local maintenance of biodiversity and biotic interactions, the canopy microclimate and plant growth, and plant physiological responses to a changing environment. Since many of these processes are different from those occurring on the forest floor, the new and valuable data that scientists are gathering within the ICCN may represent an important source of information for UNEP, multilateral environmental agreements and nations worldwide. In particular, the ICCN can be used profitably for environmental assessments and to develop early warning protocols more directly related to processes in forest canopies.

There are many scientific and political challenges to explore and conserve biodiversity on Earth, as well as to care for global ecosystems and their capacity to provide goods and services that support human livelihoods. Each network of expert scientists has the potential to help us to improve our global knowledge of life on Earth. The ICCN represents a small but significant step towards this ambitious mission.

Klaus Toepfer
Executive Director, United Nations Environment Programme
Nairobi, April 2003

PREFACE

This publication describes the development and the achievements of a network of construction cranes located in temperate and tropical forests worldwide, dedicated to the scientific study of one of the most valuable and important habitats on Earth: **forest canopies**. This booklet represents an effort to bridge the gap between academic and political domains in presenting scientific methods and data highly relevant to crucial global environmental issues, such as climate change and loss of biodiversity. Although this is the third publication under the umbrella of the United Nation Environmental Programme (UNEP) reviewing the progress of studies of the forest canopy with construction cranes (Wright & Colley, 1994, 1996), this is the first one to do so within the international context of the network.

The introductory and concluding chapters of this publication were written by the editors, with the help of colleagues. A first chapter describes succinctly the importance and value of forest canopies on Earth. The second chapter reviews the biological threats acting on forest canopies and the response by scientists and policymakers. In the third chapter, we review briefly methods of access and study of forest canopies, with an emphasis on construction cranes. Next, we introduce the International Canopy Crane Network (ICCN) and present each of the 11 crane sites currently or formerly active, plus a site which will be operational in French Guiana soon. We invited the manager(s) of each site to provide baseline information and discuss key research and findings. Most of this information is then summarized and re-considered in view of global environmental problems in the fifth chapter. The concluding chapter discusses the needs for future research and how the International Canopy Crane Network could contribute to collaborative research among crane sites. Thus, readers without particular interest in detailed accounts of research may wish to study chapters 1 to 4.1, and 5 to 6.

Recently, the Global Canopy Programme (GCP; www.globalcanopy.org) has produced an excellent handbook which details the main techniques of access and study of forest canopies (Mitchell *et al.*, 2002). We direct the reader to that reference work in order to learn more about the full range of available techniques to study forest canopies. The ICCN is the primary partner working with the Global Canopy Programme (GCP). The GCP is seeking to leverage the US$20 million in assets that are currently dedicated to forest canopy research worldwide, into a more co-ordinated and integrated program. The ten existing canopy cranes lie at the heart of this program, which also encompasses research in progress using other canopy access systems such as towers, walkways and balloons. By working closely together the ICCN and the GCP aim to raise awareness of and funding for canopy science worldwide.

The present publication serves as a companion booklet to the GCP handbook, emphasizing in greater depth the scientific achievements that construction cranes have made within the study of forest canopies and the research agenda that could be accomplished with a network of such cranes. References were kept to a minimum, since most institutions involved in the International Canopy Crane Network manage their own web site, with all the relevant information that the expert may need. The chapter dedicated to Panamanian sites is more extensive than its counterparts. This reflects in part the lengthy research activity there with two cranes, and in part the commitment to these facilities of the three editors of this book.

We thank the authors who readily provided accounts of their field sites and summarized the research being conducted there. Dieter Anhuf, Kaoru Kitajima, Margaret Lowman, Scott Miller, Vojtech Novotny and Nigel Stork improved the drafts of chapters written by the editors, while Tomas Roslin checked the whole text. Neil Springate and Mark Hanly assisted as language editor and designer, respectively. Marcos Guerra took time to search his vast archive of pictures on forest canopies to illustrate some sections of this book. Mirna Samaniego, Lina Gonzalez and Maria Luz Calderon helped to overcome other hurdles. Generously, UNEP provided funds for the design and printing of this booklet. We hope that it will be useful to biologists studying forest canopies, to others who may develop interest in this exciting field of research, as well as to environmentalists and policymakers.

Yves Basset, Vibeke Horlyck & S. Joseph Wright

Panama, May 2003

It is entirely fitting to dedicate this volume to the memory of my late and closest colleague, Alan P. Smith (1945-1993). As Research Scientist at the Smithsonian Tropical Research Institute, Alan conceived of and implemented the first use of a construction tower crane to access the canopy of a tall forest. The idea came during an interminable layover spent watching cranes construct a new passenger terminal in Miami. An initial Smithsonian grant of just $30,000 intended to fund a feasibility study was diverted to erect the first forest crane after economic sanctions imposed by the United States caused the collapse of the construction industry in Panama in 1988. Subsequent funding was obtained through the hard work of Alan and Jorge Illueca of the United Nations Environment Program who persuaded ambassadors to UNEP from the Governments of Finland, Germany and Norway that it would be a good use of their funds to dangle graduate students from a tower crane located in a Panamanian forest. Alan, Kevin Hogan, his post-doctoral fellow, and our colleague Jess Parker, of the Smithsonian Environmental Research Center, conducted the first studies of photosynthesis and canopy structure from the new crane. I returned from sabbatical in 1991 to find Alan in declining health and the crane largely unused. The opportunity to access tall trees could not be resisted. In February 1992, Alan left two large boxes of records on my desk, and without further ceremony I reluctantly became the second Scientist-in-charge of the Canopy Biology Program in Panama. Eleven years later, we have published more than 130 articles based on research conducted at two cranes in Panama, and worldwide there are eleven forest cranes located on five continents. Our accomplishments over those eleven years are a consequence of the elegance of Alan's initial idea and its embrace by colleagues from Austria, Australia, Germany, Japan, Malaysia, Panama, Switzerland, the United States, Venezuela and many other countries. From the very first, Alan's vision was global. My hope is that the present volume will help to realize that initial global vision.

S. Joseph Wright

EXECUTIVE SUMMARY

This publication describes the development and the achievements of a network of construction cranes located in temperate and tropical forests worldwide, dedicated to the scientific study of one of the important habitats on Earth: forest canopies. This booklet represents an effort to bridge the gap between academic and political domains by presenting scientific methods and data relevant to crucial global environmental issues, such as climate change and loss of biodiversity.

The 'canopy' is defined to include the aggregate of every tree crown in the forest, including foliage, twigs, fine branches and epiphytes, in short all elements of the vegetation above the ground. For sake of simplicity, 'canopy' is used here to mean the treetop region, unless specifically qualified by terms such as understorey, upper canopy and canopy surface.

On a large scale forest ecosystems provide services that include pollution mitigation, carbon sequestration, disaster prevention and regular and clean water supply. The role of forest canopies in key ecosystem processes within the biosphere, such as energy flow, biogeochemical cycles and the dynamics of regional and global climates, is crucial. In addition, forest canopies sustain countless species of animals and plants, the majority representing an unknown and unexploited resource. This reservoir of genetic diversity ensures that vital ecological processes are performed by a variety of species, rather than a few, thus maintaining the integrity of the forest ecosystem. Most of the biological activity in forests, particularly in tropical rainforests, is concentrated in the upper canopy, in comparison with the understorey. The vertical stratification of resources and organisms represents one of the key characteristics of tropical forests and their canopies.

The disruption of healthy forests and their canopies is often irreversible and leads to two obvious perils: (i) loss of forested habitats and concomitant loss of biodiversity and genetic resources; and (ii) loss of ecosystem processes such as sequestration of carbon from the atmosphere and concomitant loss of ability to buffer the effects of changes in local and global climates. Loss of species diversity itself has also direct and serious implications for the maintenance of the functioning of ecosystems.

In response to the major environmental problems facing the world today, more than 150 countries have ratified international environmental conventions to consolidate the protection of the environment. The most urgent approaches to conserve biodiversity are setting aside protected areas of land as parks and nature reserves, the establishment of biological corridors between protected forests, the restoration of degraded lands to reduce the pressure for further natural habitat conversion, as well as captive breeding and *ex situ* conservation in gene banks. In addition to the formal inter-governmental conventions and organisations, many bodies have been formed by scientists and others to address forest science and policy issues. These organisations play a vital role in synthesizing and disseminating current scientific understanding, and in formulating research agendas that foster growth of knowledge.

The study of forest canopy is associated strongly with problems of accessing the upper canopy, often 20-60m above the forest floor. Many of the earlier studies of forest canopy relied upon ground-based methods and there were few opportunities to study canopy organisms directly. During the past two decades, several methods of canopy access have broadened the ability of scientists to access the canopy. They are reviewed here, with a greater emphasis on the use of construction tower cranes to gain access to the forest canopy. This method was pioneered in Panama in 1990. The main advantages of canopy cranes are the safety and excellent access within much of the canopy and the ability to lift heavy equipment into the canopy rapidly. The main disadvantages of canopy cranes are related to the costs of purchasing, erecting and maintaining a crane, particularly in remote locations. These costs ensure that canopy cranes will complement rather than replace other methods of canopy access.

The International Canopy Crane Network (ICCN) was founded in 1997 to capitalize fully on the growing number of canopy cranes installed in forests worldwide. By replicating experiments in different forest types, the network provides the opportunity to evaluate the generality of hypotheses in a variety of situations. The main objectives of the network are to promote collaborative research on the forest canopy and to exchange students and scientists among sites. The network is composed of eleven crane facilities (one is not in operation anymore), located in eight countries. Six cranes are erected in temperate forests (Basel in Switzerland, Kranzberg, Leipzig and Solling, all in Germany, Tomakomai in Japan and Wind River in the USA) and five cranes are installed in tropical forests (Cape Tribulation in Australia, Lambir Hills in Malaysia, Surumoni in Venezuela, and Parque Natural Metropolitano and San Lorenzo in Panama). They will shortly be joined by the project COPAS (Canopy Operation Permanent Access System) in French Guiana. These sites are located in forests from different biomes and biogeographical regions, including northern coniferous forest, mixed temperate forest, decidous broad leaf forest, tropical dry lowland forest, and tropical wet lowland forest.

The first crane facility was erected in the Parque Natural Metropolitano in Panama in 1990. Another five crane facilities were installed by 1998. The average area covered by a crane is 1ha and the total area of forest covered by the network is 12ha. Despite this rather modest infrastructure, collectively, the network has been extremely successful in producing high quality science that has shed light on the maintenance of complex forest processes. Key findings are summarised here under the broad topics of biological diversity, global dimming, elevated atmospheric concentrations of carbon dioxide, and trace gas emissions.

Many studies at crane sites confirm the high specific and genetic diversity supported by canopies of temperate and tropical forests. Studies with canopy cranes often provided the first insights into the magnitude of local species richness for a range of taxa (e.g., fungi, epiphytes, beetles). For example, 1,167 species of phytophagous beetles were collected from a crane perimeter in a dry tropical forest. The same forest was estimated to contain 1,600-2,000 of such beetle species. Further, these data suggest that fewer than one in ten beetle species feed on average on a single host plant. This confirms the results of other studies which indicate that that the higher global estimates of 30-100 million species of tropical arthropods are untenable.

Species of insects, epiphytes, fungi and mosses observed near ground level typically differ from those occurring in the upper canopy. Studies at two tropical crane sites showed that insect herbivores were 2-3 times as diverse and abundant on the foliage of mature trees as on that of conspecific saplings. Overlap of herbivore species between mature trees and their conspecific saplings was very low. The maintenance of many organisms appears to depend on the presence of specific abiotic and biotic conditions along the vertical forest profile. Slight alterations of this profile (e.g., in opening up the canopy by selective logging) may change these conditions and lead to important losses of species.

Atmospheric carbon dioxide is one of the most effective greenhouse gasses, and its release by man will make a major contribution to global warming over the next century. Atmospheric carbon dioxide is, however, absorbed by plants during photosynthesis. Natural forests, which are already responsible for fixing 20% of global releases of anthropogenic carbon dioxide, may further mitigate these releases by increasing the amount of carbon absorbed as atmospheric concentrations increase inexorably. This possibility is being evaluated by using a canopy crane to release carbon dioxide experimentally in the canopy of a temperate forest. Early results from this experiment indicate that each tree species responds in its own way to increased atmospheric carbon dioxide concentrations. The loss of water as well as the uptake of carbon is altered in many species while other species show no effect. These early results suggest that anthropogenic release of carbon dioxide to the atmosphere will influence the balance between different species. Also, forests may or may not mitigate anthropogenic releases by absorbing more carbon dioxide depending on the species composition.

Light limits primary production in tall, closed canopy forests. In a phenomenon referred to as global dimming, sunlight reaching the Earth's surface has declined by 2.7% per decade since the 1950s, probably as a consequence of increases in anthropogenic particulates and cloud cover. The El Niño-Southern Oscillation (ENSO) introduces additional variation in light availability through longitudinal and latitudinal redistribution of cloud cover. This raises the possibility that light may increasingly limit net primary production by forests, particularly when the ENSO brings cloudy conditions. To evaluate this possibility, a canopy crane was used to augment light availability by positioning lights over tall canopy trees in a tropical forest. The experimental augmentation of solar irradiance by 10% caused an integrated photosynthetic response, which led to increased primary production by canopy trees. Global dimming may offset increases in net primary production expected as atmospheric concentrations of carbon dioxide increase with potentially profound effects for the global carbon cycle.

The biosphere emits (and absorbs) a variety of trace gasses, which have important effects in the atmosphere. Nitrous oxides, for example, are biologically active gasses which are also among the most effective greenhouse gasses. Nitrous oxides are emitted during decomposition of leaves in forest soils, and models of the global atmosphere incorporate rates of nitrous oxide emission measured directly from forest soils. However, living leaves are able to absorb nitrous oxides before they leave forests. Direct measurements made from a canopy crane indicate that quantitatively important amounts of nitrous oxide are absorbed by living leaves in a tropical forest so that appreciably more nitrous oxide leaves the soil than leaves the forest. These measurements will be used to determine new parameters for models of the global atmosphere.

Volatile hydrocarbons provide a second example of a biologically active gas with profound effects on atmospheric chemistry. A few temperate tree species were known to release volatile hydrocarbons to the atmosphere, particularly when leaves were heat stressed. These hydrocarbons quickly decompose into hydroxyl ions, which influence chemical reactions involving methane, ozone and other greenhouse gasses. Measurements from a canopy crane located in a tropical forest indicate that a much larger proportion of tropical trees release volatile hydrocarbons. In addition, tropical trees emitted hydrocarbons at all temperatures, not just when heat-stressed. These measurements will also improve our understanding of global atmospheric chemistry.

Each canopy crane facility is producing research that sheds new light on complex ecological processes occurring in forests and forest canopies. The International Canopy Crane Network promises to be a vehicle to attempt more ambitious studies, and to test the general relevance of new hypotheses.

1. Forest canopies and their importance

1 Forest canopies and their importance

Yves Basset, Vibeke Horlyck & S. Joseph Wright

Forest canopies

Today, the study of forest canopies is a burgeoning and exciting field, as evidenced by the ever increasing number of publications concentrating on these habitats (Nadkarni & Parker, 1994; Nadkarni *et al.*, 1996). The vitality of canopy science can be traced back to a series of studies about the canopy flora and fauna in tropical forests performed twenty years ago (Hallé *et al.*, 1978; Perry, 1978; Erwin & Scott, 1980; Nadkarni, 1981). These studies sparked continuing scientific interest in forest canopies and their inhabitants (Stork & Best, 1994; Lowman & Nadkarni, 1995; Stork *et al.*, 1997a, 1997b; Linsenmair *et al.*, 2001; Basset *et al.*, 2003a).

The term 'canopy' has been used by different authors to mean rather different things. Although it indicates the treetop region in general, its precise definition includes the aggregate of every tree crown in the forest, including foliage, twigs, fine branches and epiphytes, in short all elements of the vegetation above the ground (Nadkarni, 1995). If this highly inclusive view of 'canopy' is adopted then we need a careful set of definitions for the height sub-divisions to which we must refer for descriptive clarity (Fig. 1).

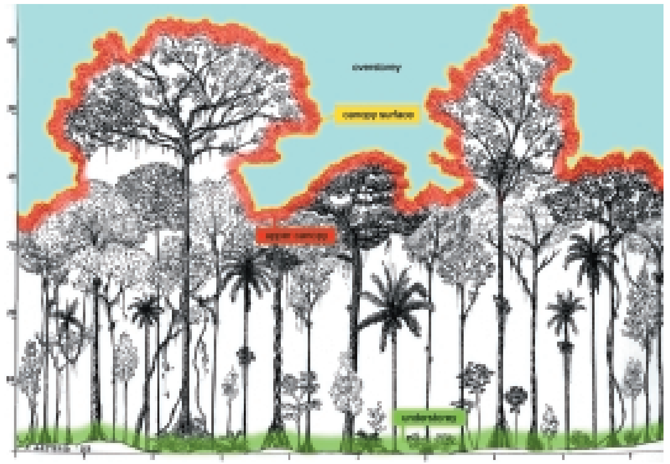

Fig. 1. Different sub-zones of the forest canopy (drawing Francesco Gattesco).

Fig. 2. Aerial view of an old growth temperate coniferous seasonal rainforest in the Thornton T. Munger Research Natural Area (see Chapter 4.2.6, photo Jerry Franklin).

The 'understorey' may be defined as the vegetation immediately above the forest floor and capable of being reached by the observer or, if such measurements are available, the zone with less than 10% light transmittance (Parker & Brown, 2000). The French word *canopée* denotes the interface between the uppermost layer of leaves and the atmosphere (Hallé & Blanc, 1990). It has been translated as 'canopy surface' (Bell *et al.*, 1999) or 'outer canopy' (Moffett, 2000). Further, the 'upper canopy' refers to the canopy surface and the volume immediately below (a few metres). This zone may be distinct only in tall, wet and closed tropical forests, where this layer experiences water condensation during the night (Blanc, 1990). Most of the biological activity and species diversity within tropical rain forests appears to be concentrated in the upper canopy, in comparison with other foliage layers (Hallé & Blanc, 1990; Parker, 1995; Basset *et al.*, 2003a). Emergent trees and the air above the canopy may be termed the 'overstorey'. Use of these different terms may be important when studying tropical forests, since their stratification is often more pronounced than that in temperate forests (Richards, 1996). For the sake of simplicity, we will equate the term 'canopy' with the treetop region, unless stated specifically.

Significance of forest canopies in ecological processes

Natural forests cover about one quarter of the global landmass, or 37 million km^2 (FAO, 2001). On a large scale forest ecosystems provide services that include pollution mitigation, carbon sequestration, disaster prevention (by stabilising soils and reducing wind and soil erosion) and

Fig. 3. Aerial view of the canopy at La Makandé forest, Gabon (photo Hirochika Setsumasa).

regular and clean water supply, just to mention a few. Many regional and global ecological processes depend crucially on the integrity of the forest canopy, which possesses many unique features (see below; Figs 2 and 3). For example, the scarcity of freshwater is a recent global problem and forests have an important role in supplying freshwater. Healthy forest influences the quantity and quality of water yielded from watersheds, moderates variation in stream flow between the high and low flows during a year, and stabilizes the soil, lowering levels of soil mass movements and surface erosion (FAO, 2003).

Forest canopies also play a key role in other ecosystem processes, including energy flows, biogeochemical cycles and the dynamics of regional and global climates. Forest canopies both control regional climate and play an important role in regulating global climate (Shukla *et al.*, 1990). The forest canopy is the principal site of energy assimilation in primary production, with ensuing intense interchange of oxygen, water vapour and carbon dioxide. Most photosynthetic activity in the biosphere occurs in the canopy and forests account for almost half of the carbon stored in terrestrial vegetation. For example, the annual net carbon production of tropical forests is 18 gigatons (a million million kilogrammes), accounting for 31% of global terrestrial photosynthesis (Malhi & Grace, 2000). Ecophysiological studies in forest canopies will be crucial to predict the impact of increasing atmospheric concentrations of carbon dioxide for carbon uptake by forests.

The low albedo[1] of the forest canopy provides ample energy for plants to photosynthesize and transpire. The high evapotranspiration[2] increases the water vapour in the air, which is released to the upper layer of the atmosphere where it cools and condenses in clouds, forming water drops. The water drops then return to the ground as precipitation. High evapotranspiration also leads to a high latent heat loss that cools the surface. In deforested areas, the higher albedo of the bare soil reduces the amount of energy absorbed at the surface. Latent heat loss is reduced severely and the surface warms, since there is no means of removing the excess energy through the transpiration of plants (Ahhuf, 2002; Foley *et al.*, 2003).

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[1] the fraction of solar radiation that is reflected

[2] transpiration: release of water vapour from leaves; evapotranspiration: evaporation from wet surfaces combined with transpiration

In addition, forest canopies, particularly in the tropics, sustain countless species of animals and plants, the majority representing an unknown and unexploited resource (Figs 4 and 5). This important reservoir of genetic diversity ensures that vital ecological processes are performed by a variety of species, rather than a few, thus maintaining the integrity of the forest ecosystem in case of disturbance. For example, pollination and seed dispersal by a variety of organisms ensure the regeneration of the forest, whereas herbivory hastens the return of nutrients to ground level and their recycling. All three processes are prevalent in the canopy.

Unique features of forest canopies

The array of tree crowns in the canopy is often heterogeneous, including trees of different species, sizes, phenologies (flowering, leaf flushing) and ages (Fig. 6). Thus, forest canopies comprise spatially complex (Fig. 7) and temporally dynamic three-dimensional structures. Such systems are particularly conducive to the stratification, niche differentiation and habitat segregation of canopy organisms, especially in the tropics.

Fig. 4. Plant diversity in the canopy on Barro Colorado Island, Panama (photo Marcos Guerra).

Fig. 5. A fungus beetle (Erotylidae) from the canopy of San Lorenzo, Panama (photo Marcos Guerra).

Many abiotic and biotic characteristics of the canopy are different from those in the underlying understorey (e.g., Hallé & Blanc, 1990; Parker, 1995). Most of the biological activity in tropical rainforests is concentrated in the upper canopy, in comparison with the understorey. The higher illumination levels in the canopy promote rapid rates of photosynthesis which, in turn, promote high plant production thereby sustaining a more abundant and diverse community of animals than in the understorey (Wright & Colley, 1996). The upper canopy receives 100% of the solar energy that penetrates the atmosphere, with just 1 to 2% of that energy eventually passing through to the understorey (Parker, 1995). Average light availability decreases up to two orders of magnitude over short distances from the external surface to a few centimetres inside the canopy (Mulkey *et al.*, 1996a). Levels of ultraviolet radiation, fluctuations of relative humidity, air temperature and wind speed are notably greater in the upper canopy than in the understorey (Blanc, 1990; Parker, 1995). Water condensation at night is frequent within the upper canopy, but absent in the understorey (e.g., Blanc, 1990). The uppermost canopy leaves are typically thicker, are more upright, have higher leaf mass and higher photosynthetic rates than understorey leaves. In closed tropical forests, the upper canopy is more akin to chaparral shrub vegetation than to rainforest understorey vegetation (Bell *et al.*, 1999). The leaf area density and the abundance of young leaves, flowers and seeds are also higher in the upper canopy than beneath (Parker, 1995; Hallé, 1998). Leaf turnover and nitrogen translocation, upon which many sap-sucking insects depend, are well marked in the upper canopy (Basset, 2001a). The leaf buds of the upper canopy appear to be extremely well protected against desiccation and herbivory (Bell *et al.*, 1999). Further, levels of secondary metabolites that defend leaves from herbivores are much higher in leaves of the upper canopy than in leaves situated at the base of the crown within individual trees (Downum *et al.*, 2001). The vertical stratification of resources and

Fig. 6. Trees blooming in Panama and emphasizing the heterogeneity of the forest canopy (photo Marcos Guerra).

organisms represents one of the key characteristics of tropical forests and their canopies, particularly in wet forests.

Differences between temperate and tropical forest canopies

There are many structural and biological differences between the canopies of temperate and tropical forests. The harshness of the climate during the winter at higher latitudes prevents year-round activity by plants and most animals. However, tropical forests and their canopies are far from representing a steady and predictable source of resources for animals. Temporal dynamics in tropical rainforests are complex, in comparison with the predictable timing of leaf, flower and fruit production at higher latitudes. Rainforest trees show a variety of leafing phenologies, from continuous leafing, to intermittent flushing to deciduous habits (Frankie *et al.*, 1974). Within the same species or an individual crown, flushing may be synchronous or not. Seasonal patterns of flowering and fruiting are equally complex and are further complicated by species that reproduce only at irregular, multi-year, intervals in mass flowering events. All this seasonal and interannual variability in resources often has drastic consequences for animals exploiting tropical forests and their canopies (Bigger, 1976; Wright *et al.*, 1999).

Fig. 7. Another form of spatial heterogeneity in tropical rainforests. A medium-sized gap in the San Lorenzo forest, Panama (photo Hirochika Setsumasa).

The structure of tropical rainforests is highly complex and is determined largely by competition for light among plant species. Light interception is almost total at ground level (0.5 - 2 percent of the illumination available in the canopy). The architecture of branching patterns varies widely among tropical tree species, which may or may not combine to form distinct forest layers. Vertical complexity and stratification are better developed in tropical forests than in temperate forests (Smith, 1973; Terborgh, 1985) and, in particular, vertical gradients in microclimatic and biotic gradients are much steeper in tropical rainforests than in temperate forests (Parker, 1995; Hallé, 1998). The quality of sun and shade leaves in tropical rainforests is therefore likely to differ substantially, even across conspecific plants, with likely consequences for specialised herbivores, including many insects.

The presence of woody lianas rooted in the ground has been called the single most important physiognomic feature differentiating tropical from temperate forests (Croat, 1978). They indeed contribute a large proportion of the leaves in tropical canopies (Avalos & Mulkey, 1999). Epiphytes (ferns, orchids, bromeliads, etc.) growing on support branches in the canopy also represent about 25% of vascular plant species in tropical countries (Nieder *et al.*, 2001). However, contrary to conventional wisdom, tree biomass in tropical rainforests is not higher than that in temperate forests, but rather identical (Enquist & Niklas, 2001). Although tropical rainforests are often taller than temperate forests, the tallest trees are temperate (Richards, 1996). In temperate and boreal forests below-ground carbon is highly significant relative to above-ground carbon, whereas this is not the case for many tropical forests, with the exception of mangrove swamps. This has important consequences for carbon sinks and sources in the context of global climate change (see next Chapter).

Although tropical rainforests cover less than 6 percent of Earth's land surface, they sustain half or more of Earth's biodiversity, and many more species than do temperate forests. The rate of endemism is also higher in tropical than in temperate forests. For example, the Malayan Peninsula contains about 7,900 plant species against Britain's 1,430. Several theories (not exempt of controversies) account for the greater plant and animal diversity in tropical than temperate forests (reviews in Turner *et al.*, 1996; Schneider *et al.*, 1999). Among others, a greater stability may have existed in the tropics, in comparison with temperate lands where recent glaciations have depleted the biota. During the Pleistocene, 10,000 years ago, climatic changes transformed many rainforests into drier savanna. Some rainforests persisted as refugia, later rejoining as the climate became more favourable, increasing species richness within. Second, tropical ecosystems may provide more ecological niches than do temperate ecosystems and thereby support more species. Third, predation and competition in the tropics may be set to levels allowing higher speciation rates. Last, high species richness in the tropics may result from solar energy controlling organic diversity in perhumid conditions. At a different time-scale, local species richness in tropical forests is also greatly enhanced by the plant succession promoted by natural forest gaps (Connell, 1979).

Still, many rainforest tree species are rare, with average densities of 0.3 to 0.6 trees per species and per hectare (Hubbell & Foster, 1986). This results in large average distance between trees of the same species that may affect pollinating and foraging animals, as well as the plants themselves. Indeed, pests or diseases are rarely a problem in mixed tropical rain forests, whilst uniform vegetation, such as plantations or temperate forests, may be heavily defoliated.

Undeniably, annual rates of leaf herbivory in tropical forests (10.9%) are significantly greater than in temperate forests (7.5%). Since increased qualitative defenses are common in tropical plants, this suggests that tropical plant species had an evolutionary history of higher herbivore pressure, and have responded with a battery of physical, chemical, mutualistic, and phenological defenses (Coley & Aide, 1991).

Another important aspect in tropical forests, differing from boreal and temperate forests, is the high degree of dioecy (i.e., the occurrence of male and female individual plants) among trees. Thus, coevolution of tree reproduction with pollinators and seed-dispersing organisms is an important and crucial functional linkage in tropical forests, which can be easily altered by global changes in climate (see next Chapter).

Forest canopies and biodiversity

Biological diversity (or biodiversity) represents the variability within and among living organisms and the systems they inhabit. Biodiversity forms the web of life of which we are an integral part and upon which we so fully depend. Biodiversity can be understood at the level of species (a group of interbreeding organisms that do not ordinarily breed with members of other groups; so far 1.5-1.8 million species have been identified, most of them being invertebrates), at the genetic level (genetic variation among individuals within each species), and at the level of ecosystems (variety of ecosystems such as deserts, forests, mountains, lakes, rivers and agricultural landscapes).

With the exceptional diversity of their arthropod communities (insects, spiders and mites), tropical forest canopies may be the most species-rich habitat on Earth, perhaps containing between 50 and 80 percent of terrestrial species (Erwin, 1983), although the soil/litter of tropical forests is another strong contender (Hammond, 1994). Scientists and the media have been long captivated by the near countless species of animals and plants sustained by tropical forest canopies. A typical hectare of rainforest may include 150-200 species of trees, with records of more than 300 species per hectare in Amazonia (Ter Steege *et al.*, 2000). Canopy trees also support many species of epiphytic plants whose roots hold fast to trees and draw water and nutrients directly from the rain, as well as arboreal mammals and reptiles, birds, bats and invertebrates. Arthropods are particularly diverse in rainforests since they exploit every niche from the soil to the canopy. One large tree in Peru yielded 43 species of ants, equivalent to the entire British fauna (Wilson, 1987). Indeed, ants represent the most regularly abundant animal group in the canopy, both in terms of numbers and biomass, whereas the most species-rich groups appear to be rove-beetles (Staphylinidae) and weevils (Curculionidae). Typically, arthropod abundance and diversity in the upper canopy are between two and four times as great as those in the understorey, particularly for insect herbivores (Basset, 2001a).

The majority of these organisms are still unknown or undescribed. Erwin (1983) termed the canopy of tropical forests 'the last biotic frontier', referring to the vast, but poorly studied, richness of organisms, particularly arthropods, resident in the canopy. Recent estimates of global diversity, based on field studies of tropical beetles and the evaluation of museum collections, scale at 4-6 million species (Novotny *et al.*, 2002). However, at present, only a fraction of that biodiversity is known to science, probably in the order of 1.5-1.8 million species. Arthropods make up the majority of this diversity, but we know desperately little about their life cycles and interactions with other species, particularly in tropical forest canopies.

Despite increasing interest in their study, the faunas of tropical canopies have been the subject of much controversy among ecologists. Even the simplest questions, such as how many arthropod species live in the canopy of various tree species and forest types, what is their resource base, or how their ecological niches evolved remain unanswered (May, 1994). Many canopy organisms show distinct physical or behavioural adaptations to arboreal life. These include the canopy root system of several tree species which tap into the humus accumulated within epiphytes; the coalescing roots of strangling figs; the prehensile tails and gliding membranes of various arboreal mammals; or the many peculiar life-cycles and specialisations (symbiotic associations) of a multitude of arthropod species. Interactions between canopy organisms are often complex, due to heterogeneous substrates and patchy food resources, often resulting in intriguing mutualisms, such as ant gardens (mutualistic balls of earth of varying size including a variety of epiphytic plant species attended and maintained by ants, Davidson, 1988). However, very little is known of most canopy organisms and their interactions with the canopy environment.

Bioprospecting in forest canopies

The need to estimate species richness and to assess our biological resources is not purely academic. The sustainable use of biological diversity does not constitute a luxury but may contribute to the alleviation of poverty (Dasgupta, 2001). Human beings are becoming more and more dependent on forest biodiversity and on the resources that forests supply. For example, chemicals such as taxol and epothilones, isolated from the Pacific yew trees and from the slime of slime moulds (Myxomycetes), respectively, have provided anti-cancer drugs (Lovejoy, 2000). Natural products are the most consistently successful source of drug leads. Natural products continue to provide greater structural diversity than standard combinatorial chemistry and so they offer major opportunities for finding novel low molecular weight lead structures that are active against a wide range of assay targets. About 39% of drugs approved between 1983 and 1994 were natural products or derived from them (Harvey, 2000). The World Health Organisation estimates that 85% of the world's population depends directly on plants for medicine (Cox, 2001). As less than 10% of the world's biodiversity has been tested for biological activity, many more useful natural lead compounds are awaiting discovery. The challenge is how to gain access to this natural chemical diversity (Harvey, 2000).

Partnerships for bioprospecting may be inhibited by lingering resentments in developing countries over past uncompensated exports of genetic material. Fortunately, institutional models are evolving in different parts of the world that show the way to a new approach to overcoming previous barriers of distrust born of centuries of inequity. A multi-dimensional partnership must be developed between the private and public sectors, with careful attention both to practical considerations of business profitability and to ethical principles of sustainability and equity (Weiss & Eisner, 1998).

Chemical defenses are often by-products of plant metabolism and include lectins, resins, alkaloids, protease inhibitors, cyanogenic glycosides, or rare amino acids. Each plant species may contain fifty or more defensive compounds in its leaves, bark or seeds. Many may be pharmacologically active, with subtle differences between individuals often due to the high genetic variation of plants. In addition, plant bioprospecting has so far targeted the understorey of tropical forests. Downum *et al.* (2001) showed that the crowns of rainforest trees produce significantly more secondary compounds at higher concentrations than do understorey saplings. The canopy samples from each species showed dramatic increases (by more than four times) in the number of compounds and their relative concentrations. The greatest number of compounds was produced from tree crowns: those exclusively from the crowns were half or more of the total number of compounds detected. Thus, bioprospecting of the canopy of tropical forests is bound to yield significant results (Hallé, 1998).

Chemical diversity is far from being restricted to plants, but plants are often a target of choice because they are sedentary and relatively easy to identify. The largest and probably most diversified reservoir of potential pharmaceuticals is represented by invertebrates. Natural products that have been derived from invertebrates include new antibiotics from ants and termites, new methods for natural pest control, and new bacteria helpful in oil spill or mining waste cleanup (see further examples in Price & Collins, 2002).

Since each tropical tree species may support from 20 to 150 species of insect herbivores alone (Novotny *et al.*, 2002), it is an understatement to write that the biological prospecting for chemical products has hardly begun.

Forests represent complex communities with a high degree of trophic interactions, where millions of years of 'chemical warfare' between plants and their herbivores have created a chemical treasure trove. Finding new species and understanding their biology means that we can discover arrays of new molecules that may be involved in new interactions. Chemical screening of these new molecules may lead to the development of new pharmaceuticals and other useful products. Our present ignorance about biodiversity in forest canopies represents an economic threat through the loss of commercial opportunities (Mitchell, 2002).

The ecological and social importance of forest canopies is fundamental. However, mankind is set on a course that has altered and continues to alter many of the crucial ecosystem processes provided by forests worldwide. In the next section, we discuss briefly the causes and outcome of these alterations, and examine how politicians and scientists have attempted to work together in order to alleviate them.

2. The conservation of forest canopies: policy and science

2 The conservation of forest canopies: policy and science

Yves Basset, Vibeke Horlyck & S. Joseph Wright
With contributions from Dieter Anhuf, Andrew Mitchell & Nalini Nadkarni

Fig. 8. Undisturbed forests and selective logging in a tropical rainforest in Mabura Hills, Guyana: (a) typical understorey of an undisturbed forest; (b) E. Charles and L. LaGoudou in a large natural gap; (c) W. Jarvis (Guyana Forestry Commission) felling Greenheart trees; (d) result of intense selective logging (photos Yves Basset).

The demise of healthy forests

Forest ecosystems are fragile, particularly in the tropics. To perform adequately the ecosystem processes mentioned in the first chapter, the integrity of the forest and of its canopy must be preserved. This is best understood by considering tropical rainforests and their demise. Although most tropical rainforests grow on nutrient-poor soils, their net primary production is the highest of any natural system, averaging 925g m^{-2} yr^{-1} (9.25 tons of biomass per hectare; Amthor, 1998). Nutrients are efficiently recycled via capture from rainfall, which may comprise as much as 1-15kg of nitrogen and 0.3-0.4kg phosphorus per hectare per year (Hedin *et al.*, 1995), and rapid decomposition and re-uptake by plants. In addition, roots may sometimes penetrate to the depth where the decomposition of rocks and saprolites (i.e., deposits of clay and disintegrating rock) frees nutrients.

Rainforest regeneration and continuity is assured through the important processes of pollination and seed dispersal, both performed by rainforest animals primarily dwelling in the canopy. Their loss in strongly disturbed rainforests affects severely the regeneration capacity of the forest (Wright & Duber, 2001). Wind pollination, common in temperate regions, is often much rarer in tropical rainforests, where 90% of rainforest plants are insect-pollinated, with nectar the reward for pollinators (e.g., Roubik, 2000).

The clearing and burning of rainforests concentrates nutrients of the above ground vegetation in the soil. Some nitrogen and sulfur are lost during burning, but large quantities of other nutrients are deposited in ash. Leaching, due to heavy rainfall, washes these nutrients to soil depth beyond the shorter roots of new grasses or shrubs. This severely disrupts the nutrient cycle, leaving barren, petrified tracts which remain unproductive or require the application of costly fertilizers. Further, clearing and removal of logs by heavy machinery result in soil compaction, water runoff and, eventually, soil erosion. In addition, when a large area of forest is cleared, the soil becomes drier and warmer and many microbes that help trees to fix nitrogen and phosphorus are killed (Fig. 8).

The implications of large-scale deforestation may be severe (see below for specific mechanisms). For example, simulations suggest that conversion of the Amazon basin from forest to pasture would cause a permanent warming and drying of South America, because the shallower roots of grasses access less water, leading to less evapotranspiration and greater energy dissipation as sensible heat (Shukla *et al.*, 1990). Large scale forest fires may also prevent rain from falling when it would otherwise fall heavily, by releasing smoke that decreases the ability of water droplets to condense. This effect could reduce total rainfall in certain areas and affect global-scale weather circulation patterns (Rosenfeld, 1999).

Biological threats to forests and their canopies

The disruption of the fragile equilibrium described above is often irreversible and leads to two obvious perils: (i) loss of forested habitats and concomitant loss of biodiversity and genetic resources; and (ii) loss of ecosystem processes such as sequestration of carbon from the atmosphere and concomitant loss of ability to buffer the effects of changes in local and global climates. Note that loss of species diversity itself also has direct and serious implications for the maintenance of the functioning of ecosystems (see section on loss of biodiversity).

In the last 8,000 years about 45% of the Earth's original forest cover has disappeared, cleared mostly during the past century. In 2000 there were 3,869 million ha of forests world-wide. The decline in forest cover has been 9.4 million ha per year since 1990, mostly including primary forests in the tropics (FAO, 2001). Annual deforestation rates of tropical forests range between 1 and 4% of their current area (Dobson *et al.*, 1997). Only 9.5% of the world's closed forests enjoy some form of protected status (FAO, 2001). Tropical deforestation is determined by different proximate causes and underlying driving forces acting in various combinations in different geographical regions (Geist & Lambin, 2002). The principal causes of tropical deforestation in order of decreasing importance follow:

(1) extension of overland transport infrastructure (road construction);
(2) clear-cutting for timber and pulp;
(3) plantation cultivation;
(4) cattle-ranching and farming;
(5) selective logging of particular tree species;
(6) shifting cultivation (slash-and-burn);
(7) extraction of fuel wood; and
(8) natural disasters, including localized landslides and fires.

Factors (1), (2) and (4) lead to habitat fragmentation and destruction, factor (3) creates large areas of secondary regrowth, factor (5) leads to an irregularly structured patchwork of primary and secondary forests, factors (6) and (7) create small patches of secondary growth, whilst factor (8) leads to secondary regrowth and natural succession. Contrary to widely held views, case studies suggest that shifting cultivation is not the primary cause of deforestation (Geist & Lambin, 2002).

The main forces driving tropical deforestation include economic factors (such as commercialization and the growth of timber markets), institutional factors (such as land use policies), technological factors (such as agrotechnological change in land use intensification and extension), cultural or sociopolitical factors (such as public attitudes, values and beliefs), and demographic factors (such as immigration of colonizing settlers). Deforestation cannot be stopped and reversed without addressing these and other fundamental problems, as well as developing more sustainable forms of forest management. Contrary to a common misconception, population increase due to high fertility rates may not always be a primary driver of deforestation at a local scale and over a time period of several decades (Geist & Lambin, 2002).

The ever-increasing human damage to tropical rainforests shows no sign of slowing down. It is probable that, in a few decades, large tracts of rainforests will only remain in the Guianas, upper Amazon, Congo Basin and New Guinea (FAO, 2001).

Loss of biodiversity and genetic resources

The following factors represent the main causes of the loss of biodiversity in forests (Secretariat of the Convention on Biological Diversity, 2002):

- habitat loss, fragmentation and degradation (land-use changes);
- alien species invasion;
- over-harvesting of forest resources (logging, bush meat); and
- climate change.

Much controversy exists regarding rates of forest and biodiversity loss. The figures often cited are 50 ha per minute and 17,500 species per year, respectively (Wilson, 1990). Current global extinction rates are 100 to 1,000 times greater than pre-human levels (Lawton & May, 1995) and 20% of the species of mammals and 10% of the species of birds are currently threatened by extinction (Vitousek *et al.*, 1997a). Current estimated rates of extinction for higher life-forms in tropical rainforests are 1-10% of these species in the next 25 years (or 1,000 to 10,000 times background rates; Heywood & Watson, 1995). Due to hunting by humans, many tropical rainforests are already emptied of their large animals, although displaying intact vegetation (Redford, 1992). In addition, the number of extinct and endangered forest species can be expected to rise due to an 'extinction debt', and continued habitat loss, fragmentation, invasive species and over-exploitation. The extinction debt is significant as many extinctions will happen in the future as a result of the deforestation and degradation which have already occurred (Brooks *et al.*, 1999). During the past 500 million years, Earth has experienced five periods of mass extinction. However, none of those approached the present human-driven extinction, often dubbed as the 'sixth extinction'.

Extinction rates for the largest component of biodiversity, invertebrates, are largely unknown. Entomologist Terry Erwin (1983) suggested that there may be as many as 30 million species of arthropods, instead of the previously estimated 1.5 million. Further work indicated that Erwin's estimate is probably too high by a factor of 5 or 6 (Novotny *et al.*, 2002). Nevertheless, the merit of Erwin's estimates is to have attracted considerable attention to the vast reservoir of genetic diversity represented by arthropods thriving in tropical rainforest canopies. The loss of locally adapted populations within species, and of genetic material within populations, is a human-caused change that reduces the resilience of species and ecosystems while precluding human use of the library of natural products and genetic material that they represent (Vitousek *et al.*, 1997a). As Erwin (1988) stated, discussing the loss of rainforests, "no matter what the number we are talking about, whether 1 million or 20 million (arthropod species), it is massive destruction of the biological richness of Earth".

Predictions for the year 2100 (Sala *et al.*, 2000) suggest that the key drivers affecting biodiversity in terrestrial ecosystems will be, in order of decreasing importance, land-use change, climate change, nitrogen deposition and acid rain, invasion by alien species, and increased carbon dioxide concentration. For tropical forests, the main driver will remain land-use change, with relatively small effects due to other drivers. For northern temperate forests, most drivers will have important effects, with the main contribution from nitrogen deposition and acid rain.

Tropical forests are extraordinarily rich in endemic species and so loss of tropical forests tends to result in large numbers of species becoming threatened. There are many species that depend, for instance, on standing dead trees or on dead wood lying on the forest floor, and both of these habitats tend to be absent in highly managed forests. Furthermore, many extinctions can occur even if fragments of undisturbed forest remain, and the connectivity among fragments will hence be important in allowing animals and plants to recolonise temporarily lost ground (Secretariat of the Convention on Biological Diversity, 2002).

Global climate change

On a global scale, human alteration of natural habitats is substantial and growing. Between one third and one half of the land surface has been transformed by human action; the carbon dioxide concentration in the atmosphere has increased by nearly 30% since the beginning of the Industrial Revolution; more atmospheric nitrogen is fixed by humanity than by all natural terrestrial sources combined; and more than half of all accessible surface fresh water is put to use by humanity. We are changing Earth more rapidly than we are understanding it (Vitousek *et al.*, 1997a).

Global change is much more than climate change. It is real, it is happening now and it is accelerating (Parmesan & Yohe, 2003). Climate change per se can be defined as the variation in either the mean state of the climate or in its variability, persisting for an extended period, typically decades or longer. It encompasses temperature increases ('global warming'), sea-level rise, change in precipitation patterns, changes in ice and snow cover, and increased frequencies of extreme events. Global circulation models suggest that by the end of the 21st century, global climate could be 1.4 to 5.8°C warmer than today. This represents a faster change than any seen in the last 10,000 years. These models also suggest that climate change probably represents the greatest threat to the boreal region world-wide. Sea levels are projected to rise by 9cm to 88cm and by the year 2080, about 20% of coastal wetlands could be lost. Increases in global mean precipitation and in the frequency of intense rainfall are predicted, although some already dry areas are expected to become drier. Recent trends in the increased frequency and magnitude of the El Niño-Southern Oscillation (ENSO) phenomena, which leads to severe floods, droughts and fire outbreaks in both the tropics and sub-tropics, are projected to continue (Gitay *et al.*, 2002). Beside the redistribution and loss of species discussed in the next section, climate change is also expected to result in increases in pest invasion and in increased frequency of forest fire in many forest ecosystems (Easterling *et al.*, 2000).

The weight of scientific evidence suggests that the observed changes in climate are caused, at least in part, by human activities, primarily the burning of fossil fuels (carbon-based fuels from fossil carbon deposits, including coal, oil and natural gas) and changes in land cover. These activities are modifying the concentration of 'greenhouse gases' (mainly water vapour, carbon dioxide, methane, nitrous oxide and ozone) and of anthropogenic aerosols in the atmosphere. Greenhouse gases absorb infrared radiation, emitted by the Earth's surface, by the atmosphere itself and by clouds. This radiation is then re-emitted to all sides, including downward to the Earth's surface. Thus, greenhouse gases trap heat within the surface-troposphere (the lowest part of the atmosphere) system. This is called the 'natural greenhouse effect'. Without this natural effect, the Earth's average temperature would be 18°C below zero and Earth would probably be a lifeless, frozen wasteland. An increase in the concentration of greenhouse gases leads to an increased infrared opacity of the atmosphere. This causes an imbalance that can only be compensated for by an increase of the temperature of the surface-troposphere system, or 'global warming'. This is the 'enhanced greenhouse effect'. Because most greenhouse gases remain in the atmosphere for a long period of time, even if emissions from human activities were to stop immediately, the effects of accumulated past emissions would persist for centuries (Gitay *et al.*, 2002).

Humanity adds CO_2 (carbon dioxide) to the atmosphere by mainly mining and burning fossil fuels (in automobiles, industry and electricity generation), and by converting forests and grasslands to agricultural ecosystems (carbon represents 50% of the dry weight of a tree). The net result of both activities is that organic carbon from rocks, organisms and soils is released into the atmosphere as CO_2. The atmospheric concentration of CO_2 (as judged from air bubbles extracted from ice cores, such as the 450,000-year record from the Vostok ice core: Petit *et al.*, 1999) was nearly stable around 280ppm (parts per million) for thousands of years until about 1800 and then increased exponentially up to current levels of 368ppm (an increase of 31±4%). The projected concentrations for the year 2100 are 540 to 970ppm. Fossil fuel combustion now adds 5.5 ± 0.5 gigatons (a million million kilogrammes) of CO_2 to the atmosphere annually, mostly in economically developed regions of the temperate zone. Carbon dioxide is currently responsible for over 60% of the 'enhanced' greenhouse effect (Vitousek *et al.*, 1997a; Gitay *et al.*, 2002).

Containing 49% of the total carbon stock of forests worldwide, boreal forests represent the primary terrestrial carbon pool, far ahead of tropical and temperate forests. More than 84% of the carbon contained in boreal forests is stored in soils. Forests of mid- and high latitudes are estimated to be net sinks of carbon (0.7 ± 0.2 gigaton per year), mostly because of the uptake by rapidly growing young forests (Brown *et al.*, 1996). Evidence suggests that 'old-growth' forests continue to sequester more carbon than managed forests. In this respect, the boreal biome plays a key role in climate regulation. The issue is more complex with tropical forests since they absorb carbon and at the same time release it in the atmosphere because of deforestation and fires. Burning of forests is considered to contribute between 20 and 40% of total CO_2 emissions world-wide. Houghton *et al.* (2000) estimate that the Brazilian Amazon region during the years 1988-1998, on average, was approximately carbon neutral, but was able to become a sink or a source of carbon of about 0.2 gigaton per year, depending on the year (fire increased in dry years). In recent years, the biomass of tropical forests has been increasing, providing a modest negative feedback on the rate of accumulation of atmospheric CO_2 (Philips *et al.*, 2002). However, recent studies suggest that temperatures experienced by canopy leaves may be close to the point at which respiration exceeds photosynthesis so that net production of CO_2 results. Positive feedback between higher temperatures and CO_2 production by tropical forests could be catastrophic by resulting in accelerated increases in global CO_2 levels (Clark *et al.*, 2003).

The growth of most plants is enhanced by elevated CO_2, but to different extents. Further, elevated CO_2 can change the palatability of leaves and either promote or discourage insect herbivores. Therefore, increased atmospheric CO_2 may change the competitive balance between species that differ in various biological characteristics, such as photosynthetic pathways. The fact that increased CO_2 affects species differentially means that it is likely to drive substantial changes in the species composition and dynamics of all terrestrial ecosystems, including forest canopies.

The cycle of nitrogen (N) includes a vast atmospheric reservoir (N_2) that must be fixed (combined with carbon, hydrogen or oxygen) before it can be used by most organisms. Before the extensive human alteration of the N cycle, 90 to 130 million metric tons of N were fixed biologically on land each year. Human activity has altered the global cycle of N by fixing N_2, deliberately for fertilizer (including industrial fixation and cultivation of legume crops that fix N symbiotically), and inadvertently by fossil fuel combustion. Overall, human activity adds at least as much fixed N to terrestrial ecosystems as do all natural sources combined. Alteration of the N cycle has many consequences, including, in the atmosphere, an increase in concentration of the very stable greenhouse gas nitrous oxide (N_2O) by 17±5% for the years 1750 to 2000; increase in fluxes of reactive N gases; and a substantial contribution to acid rain and to the photochemical smog that afflicts urban and agricultural areas throughout the world (Vitousek *et al.*, 1997a; Gitay *et al.*, 2002).

The eutrophication and acidification powers of ammonia (NH_3) and ammonium (NH_4+) deposition from the air has been well known since the mid 1980s. It is considered one of the main causes for forest decline in Central Europe. Forests 'comb' these substances from the air and concentrate their deposition. Trees and other plants take up ammonia and ammonium directly from the air via their stomata and assimilate them into their leaves. Algae or lichens in the canopy also assimilate these nitrogen compounds directly. Deposition and assimilation of NH_3 and NH_4+ trigger eutrophication of the ecosystem with a nutrient that in the past has been in short supply in most temperate forests. This eutrophication occurs via leaf and litter fall and by the decomposition of this organic material through the activities of soil organisms (Ellenberg & Nettels, 2001).

In addition, the atmospheric concentration of another greenhouse gas, methane (CH_4), increased by 151±25% from the years 1750 to 2000, primarily due to the emission from fossil-fuels, livestock, rice agriculture and landfills. Ozone (O_3) concentration also increased in the lower atmosphere primarily due to production of chemical reactions involving naturally occurring gases and gases from pollution sources, such as automobile exhaust fumes. Increased levels of ozone are generally harmful to living organisms because ozone reacts strongly to destroy or alter many other molecules. However, the surface production of ozone does not contribute significantly to the abundance of ozone in the stratosphere (upper atmosphere), which is considered to be beneficial (see below) (Gitay *et al.*, 2002; World Meteorological Organization, 2002).

Humanity has also released in the global environment high quantities of synthetic organic chemicals that may be toxic and persistent, such as the insecticide DDT. Few of these chemicals are tested adequately for health hazards or environmental impact. The persistent and volatile chlorofluorocarbons (CFCs), of widespread use as refrigerants, aerosol propellants, solvents and foaming agents, are not toxic. However, CFCs drive the breakdown of ozone in the stratosphere. Stratospheric ozone absorbs much of the Sun's ultraviolet-B radiation, which is biologically harmful and may increase the incidence of skin cancer and other genetic mutations. Ozone depletion was first noticed over Antarctica in the early 1980s (Farman *et al.*, 1985). The severe depletion of ozone there, because of the special weather conditions there, became known as the 'ozone hole'. The ozone layer has also been depleted by an average of 3% over the globe since 1980. The depletion, which exceeds the natural variation of the ozone layer, is very small near the equator and increases with latitude toward the poles (World Meteorological Organization, 2002).

Effects of global climate change on biodiversity

Current measured effects of global climate change include significant range shifts of species averaging 6.1km per decade towards the poles and significant mean advancement of spring events by 2.3 days per decade (Parmesan & Yohe, 2003). However, the capacity of forest associations and individual component species/populations to adapt to climate change has been greatly diminished by forest fragmentation, with reduced gene flow and migration options. Climate change in combination with increasing fragmentation and loss of forest types is likely to cause extinction of many species. More mobile, widespread, genetically variable species with short generation times will be best able to adapt and survive accelerated climate change (Holt, 1990). Changes in community composition are also likely to result not only from direct abiotic limits to species' dispersal, establishment or persistence, but also from alterations in complex interactions between species and their mutualists, competitors, predators or pathogens. Another consequence of global climate change is the modification of the genetic composition of populations and species. Changes in the amount of pollinators or animals dispersing seeds and fruits will have effects on the genetic structure of host plant populations (Pacheco & Simonetti, 2000). Projected changes in climate would cause a migration towards the poles of certain species by hundreds of kilometres and an upward altitudinal displacement by hundreds of metres. Many species will not be able to redistribute themselves fast enough to keep pace with the projected changes in climate. Large quantities of carbon may be emitted into the atmosphere during transitions from one forest type to another if mortality releases carbon faster than regeneration and growth absorbs it. For example, north temperate tree species will have to disperse 160-640 km northward in order to find sites with a hospitable climate, whereas paleoecological evidence suggest that in the past, most plant species migrated at only 20-200 km per century (Heywood & Watson, 1995).

The functioning of ecosystems involves the movement and transformation by the biota of millions of tons of material per year between organic and inorganic pools through the processes of decomposition, nutrient mineralization, assimilation and production. There is a growing concern that changes in the number and spatial distribution of species can have important effects on ecosystem functioning, whereby species-poor ecosystems may perform differently or less efficiently than the more-species rich systems from which they are derived. Diversity is functionally important because it increases the probability of including species that have strong ecosystem effects and because a diverse range of traits provides opportunities for more efficient resource use in a variable environment. Therefore, current global environmental changes that affect species composition and diversity are profoundly altering the functioning of the biosphere (Chapin *et al.*, 1997).

There is evidence to suggest that small, critical changes in biodiversity may have an adverse effect on the average rates of ecosystem processes such as primary production and nutrient retention. Over long time periods, modelling also suggests that high species diversity might allow the reliable functioning of ecosystems by buffering the impact of species loss and of the extreme fluctuations brought about by global change. Species that may be redundant for an ecosystem process at a given time may no longer be redundant through time. Species whose loss is thought to have large functional consequences (keystone species) are those that modify the availability of limiting resources, that affect the disturbance regime, or that alter the trophic structure of the impacted ecosystem. Of increasing concern is the loss of species that have similar effect on the ecosystem, but differ in their responses to a variable environment. Loss of such species may reduce ecosystem resilience and the capacity to adjust to ever-increasing rates of environmental change (Chapin *et al.*, 1997).

In this context, tropical and boreal forests appear rather different. The time dimension is particularly important for tropical forests. Only 50 tree generations (10,000 years) have elapsed since the last glacial retreat, when temperatures were considerably cooler. Because of the long lifespan of the dominant trees, it may be difficult to estimate the dramatic and long-term impact of the shifting balance of herbivores and predators in this system on plant reproductive biology, and hence on the structure and function of the forest. In boreal forests, low diversity and low redundancy are key factors. Low species richness translates into low numbers of species of any functional type. Thus the impact of the removal of one species can be great (Mooney *et al.*, 1996).

Responses: policy

In response to the major environmental problems facing the world today, more than 150 countries have ratified international environmental conventions to consolidate the protection of the environment. Below, we briefly introduce conventions (as the highest level policy body) and United Nations organisations that have a strong relationship with the study of forest canopies.

Convention on Biological Diversity (CBD)

The importance of the biodiversity challenge was universally acknowledged at the United Nations Conference on Environment and Development, which met in Rio de Janeiro in 1992, and through the development of the Convention on Biological Diversity (www.biodiv.org). In ratifying the Convention, the Parties have committed themselves to undertaking national and international measures aimed at achieving three objectives: the conservation of biological diversity; the sustainable use of its components; and the fair and equitable sharing of benefits arising out of the utilization of genetic resources. So far, the CBD has been ratified by 187 countries.

The Convention's ultimate authority is the Conference of the Parties (COP), consisting of all governments that have ratified the treaty. The COP can rely on the expertise and support from several other bodies, including the Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA), the Clearing House Mechanism and the Secretariat of the Convention on Biological Diversity (SCBD), based in Montreal. The SBSTTA is composed of experts from member governments competent in relevant fields.

Since the adoption of the Convention, the COP has met several times and, on each occasion, through its decisions, has taken steps to translate the general provisions of the Convention into practical action. This process has initiated national action plans in over 100 countries, raised awareness about biodiversity and led to the adoption of the Cartagena Protocol on Biosafety, a landmark treaty which provides an international regulatory framework for the safe transfer, handling and use of any living modified organisms resulting from modern biotechnology. Another major achievement was the adoption of the Bonn guidelines on access to genetic resources and the fair and equitable sharing of the benefits arising from their utilization (UNEP, 2002). The COP has launched a number of thematic programmes covering the biodiversity of inland waters, forest, marine and coastal areas, dry and agricultural lands. Cross-cutting issues are also addressed on matters such as the control of alien invasive species, strengthening the capacity of member countries in taxonomy, and the development of indicators of biodiversity loss.

Following successful lobbying by the Global Canopy Programme (see below, section on consensus), the following additions have been included in the 'Workplan on Forests' of the Convention on Biological Diversity, approved in April 2002 (UNEP, 2002; Secoy, 2002). For the first time the Convention now specifically calls for a greater emphasis on the forest canopy and the investigation of its interface with the atmosphere. This has created a mandate for governments to support canopy research and is a highly significant development for canopy science and conservation. The text reads as follows:

Programme Element 3, Goal 3, Objective 1, Activity b.
"Develop and support research to understand critical thresholds of forest biological diversity loss and change, paying particular attention to endemic and threatened species and habitats including forest canopies".

Programme Element 1, Goal 2, Objective 3, Activity a.
"Promote monitoring and research on the impacts of climate change on forest biological diversity and investigate the interface between forest components and the atmosphere".

Convention-related activities by developing countries are eligible for support from a financial mechanism called the Global Environment Facility (GEF). GEF projects, supported by the United Nations Environmental Programme, the United Nations Development Programme (UNDP) and the World Bank, help forge international cooperation and finance actions to address four critical threats to the global environment: biodiversity loss, climate change, depletion of the ozone layer and degradation of international waters. By the end of 1999, GEF had contributed nearly $1 billion for biodiversity projects in more than 120 countries.

A fundamental challenge for the Convention lies in the broad scope of its three objectives. This requires cooperation with many different actors, such as regional bodies and organizations. The Parties have committed themselves to a more effective and coherent implementation of the three objectives of the Convention, to achieve by 2010 a significant reduction of the current rate of biodiversity loss at the global, regional and national level as a contribution to poverty alleviation and to the benefit of all life on Earth (Secretariat of the Convention on Biological Diversity, 2000).

The SCBD has identified several major challenges to implementing the CBD (Secretariat of the Convention on Biological Diversity, 2000) and the following are particularly relevant to the International Canopy Crane Network (ICCN), presented in this publication:

(a) increasing the capacity to document and understand biodiversity, its value, and threats to it;
(b) building adequate expertise and experience in biodiversity planning; and
(c) improving education and public awareness about the value of biodiversity.

With regard to (a), as will be argued in the next chapter, canopy construction cranes represent important tools to discover and study *in situ* the vast but mostly unknown biodiversity that thrives in forest canopies. With regard to (b), the ICCN represents collectively one of the best panels of experts with experience on canopy biodiversity. With regard to (c), educational lifts in the canopy with canopy cranes represent one of the best strategies to attract the attention of the public on the important reservoir of biodiversity in forest canopies.

United Nations Framework Convention on Climate Change (UNFCCC)

The ultimate objective of the UNFCC (http://unfccc.int), which was adopted in 1992, entered into force in 1994 and has so far been signed by 166 countries, is the stabilization of greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system. The Kyoto Protocol to the UNFCCC was adopted in 1997 and defines reduction targets for greenhouse gas emissions by industrialized countries which have been primarily responsible for human-induced greenhouse gas emissions. So far, the Kyoto Protocol has been signed by 84 countries. It provides both for mitigation of climate change (included through reduced emissions of greenhouse gases, and increased removals of such gases from the atmosphere by sinks, such as forests), and for adaptation to the adverse effects of climate change. These activities must be consistent with the conservation and sustainable use of biological diversity. While individual country commitments vary (only industrialized countries have strict commitments), the Protocol calls for an overall reduction of greenhouse gases emissions by 5% from 1990 levels by the 2008-2012 period. This appears to be insufficient. To ensure that further temperature increases are not more than 0.1ºC per decade would require industrialized countries to reduce emissions of greenhouse gases by at least 30-55% from 1990 levels by 2010 (Gitay *et al.*, 2002).

In practice, the Kyoto Protocol requires monitoring of greenhouse gas removals and emission from human-induced afforestation (planting of new forest on lands that historically have not contained forest), reforestation (planting of forests on lands that have previously contained forests but that have been converted to some other use) and deforestation since 1990. Assessment of emissions and of climate impacts, particularly on carbon sinks and sources, requires clear definition of deforestation and reassessment of the fate of carbon in such systems.

In this context, the maintenance and the extension of research facilities providing access, measurements and experimentation *in situ* at the interface between the atmosphere and the forest, such as the canopy cranes of the ICCN, are of crucial importance to develop sound scenarios of carbon sequestration. This is further emphasized by the need to scale up from experiments performed in chambers to intact ecosystems and forest stands. Field chambers create artificial environmental conditions and plants grow often differently inside than outside. These chambers can accommodate young trees, but not mature tree stands or forest ecosystems. Hence the development of Free-Air CO_2 Enrichment (FACE) technology for controlling an elevated CO_2 concentration in the open air was a critical advancement enabling the study of CO_2 effects on ecosystems (Norby *et al.*, 2001). Since the CO_2 concentration at the upper canopy level, where the greatest effect of CO_2 on photosynthesis is expected, is much lower than that at ground level, experiments must release CO_2 near the top of the canopy (Norby *et al.*, 2001). The canopy cranes of the ICCN allow the convenient implementation of such experiments (see Chapter 4.2.1, notably).

Vienna Convention for the Protection of the Ozone Layer

In 1985, the above treaty was signed by 20 nations in Vienna (www.unep.ch/ozone/vienna.shtml). The signing nations agreed to take appropriate measures to protect the ozone layer from human activities. In response to growing concerns, the Montreal Protocol on Substances that Deplete the Ozone Layer was signed in 1987 and ratified in 1989. So far, 180 countries have ratified the Protocol, which establishes legally binding controls for developed and developing nations on the production and consumption of halogen source gases known to cause ozone depletion. The Montreal Protocol provides for the transitional use of hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) as substitute compounds of the dangerous chlorofluorocarbons (CFCs, see section on global change, above). However, HCFCs and HFCs also contribute to greenhouse gases and they are also monitored by the Kyoto Protocol. As a result of the Montreal Protocol, the total abundance of ozone-depleting gases in the atmosphere has begun to decrease in recent years. If the nations of the world continue to follow the provisions of the Protocol, the decrease will continue throughout the 21st century. By mid-century, the effective abundance of ozone-depleting gases should fall to values present before the Antarctic 'ozone hole' began to form in the early 1980s (World Meteorological Organization, 2002).

The interest of the ICCN in the ozone debate clearly involves tropospheric (i.e., in the lower atmosphere) ozone, not stratospheric ozone (see global change, above). In a fashion similar to FACE projects, canopy cranes may permit *in situ* experiments in the canopy, which can help to understand the negative effects of ozone close to the Earth's surface and how to mitigate them (see Chapter 4.2.2).

United Nations Environment Programme (UNEP)

The mission of UNEP is "to provide leadership and encourage partnership in caring for the environment by inspiring, informing, and enabling nations and peoples to improve their quality of life without compromising that of future generations" (www.unep.org). At the forefront of the global environmental effort, UNEP has negotiated the three conventions discussed above, which are particularly relevant to the study of forest canopies (Secoy, 2002). These conventions have all established research priorities many of which involve studies of forest and, in particular, processes which take place in the canopy or between the biosphere (the canopy) and the atmosphere (Stork, *et al.*, 1997a). In addition, two canopy access facilities in Panama (Chapter 4.3.5) were partly funded by the governments of Belgium, Denmark, Finland, Germany and Norway through the clearinghouse mechanism of UNEP. UNEP also generously contributed funds for the production of three booklets summarizing various aspects of canopy research (Wright & Colley, 1994, 1996; this booklet).

Intergovernmental Panel for Climate Change (IPCC)

Recognizing the problem of potential global climate change, the World Meterological Organization (WMO) and UNEP established the IPCC in 1988 (www.ipcc.ch). IPCC reviews current information on climate change and suggests strategic responses. The IPCC does not carry out research nor does it monitor climate related data or other relevant parameters. It bases its assessment mainly on peer reviewed and published scientific/technical literature. The first IPCC assessment report was completed in 1990 and played an important role in establishing the United Nations Framework Convention on Climate Change (UNFCCC, see above). The second IPCC assessment report was completed in 1995 and provided key input for the preparation of the Kyoto Protocol to the UNFCCC.

The third and latest assessment report from the IPCC was finalized in 2001 and concluded that the evidence for human influence on the global climate is now stronger than ever before. It also confirmed that many cost-effective solutions to rising greenhouse gas emissions are available today. In many cases, however, governments will need to address various institutional, behavioural and other barriers before these solutions can realize their potential. The report also emphasized the need for international cooperation, especially through strengthening global observational networks and improving the ability to monitor, assess and gather data. Meeting these needs will narrow the disparity between current knowledge and policymaking needs and thus a very high priority is given to improvement of communication between scientists and policymakers.

Responses: science

The most urgent approaches to conserve biodiversity are setting aside protected areas of land as parks and nature reserves, the establishment of biological corridors between protected forests, the restoration of degraded agricultural and industrial lands, to reduce the pressure for further natural habitat conversion, as well as captive breeding and *ex situ* conservation in gene banks (Dobson *et al.*, 1997). Further, effective conservation of biodiversity without integrating socio-economic factors is doomed to failure (Janzen, 1998). Restoring complex tropical wild lands, for example, is first and foremost a social endeavor as the technical issues are far less challenging (Janzen, 1991, 1998; see also Jennings *et al.*, 2000).

Scientists have resorted to long-term monitoring of climate in order to be able to predict global changes (e.g., the IPCC, above), but also to long-term ecological research in order to understand better the causes and consequences of such changes. For example the Long Term Ecological Research (LTER) programme in the USA includes a network of research sites that concentrate on similar core research areas, including many of the research themes exposed in the above sections (Hobbie, 2003). Long-term and cross-scale ecological research is particularly stimulating to understand the relationships between biodiversity and ecosystem functioning, as it allows extrapolation of results to longer time scales and larger spatial scales - those of ecosystems (Symstad *et al.*, 2003).

Complex computer simulations are then essential for understanding global climate change. The most detailed projections are based on coupled atmosphere-ocean general circulation models (e.g., Bousquet *et al.*, 2000; Cox *et al.*, 2000; Cramer *et al.*, 2001). Large climate modeling experiments consume enormous computing resources, are expensive, and the interpretation of their results often requires significant additional efforts. Their complexity stems from the necessity of accounting for millions of entangled local, regional and global processes and detecting a real signal of climate change against chance fluctuations. Models also need to account for positive reactions in the biosphere triggered by a changing climate. These feedbacks involve water vapour, snow and ice, and may amplify the direct response to greenhouse gas emissions. A supplementary difficulty is to integrate the impact of life on the process of energy exchange between the atmosphere and the earth's surface (Cox *et al.*, 2000; Betts, 2000). This complex subject is beyond the scope of this essay.

Another response of scientists has been to database most of biodiversity information, so that the digital information can be summarized, if needed, and returned to scientists, legislators, teachers or children. Such examples include the efforts of the:

- Global Biodiversity Information Facility (GBIF; http://www.gbif.org/), an intergovernmental organization;
- 'Comisión nacional para el conocimiento y uso de la biodiversidad' (CONABIO) in Mexico (http://www.conabio.gob.mx/);
- National Biodiversity Institute in Costa Rica (Gámez, 1991) with the Atta database (www.inbio.ac.cr/atta/); and
- EcoPort Consortium under the auspices of the University of Florida, the Food and Agricultural Organisation (FAO) of the United Nations and the National Museum of Natural History of the Smithsonian Institution. Under the patronage of Nelson Mandela and Edward O. Wilson, the EcoPort database (www.ecorport.org) functions as a 'consilience engine' that empowers a global network of password-enabled authors to record their knowledge of biodiversity in a communal database. As a Global Public Good, the service operates under a copy-left regime and access to its contents is free to the general public for educational and not-for-profit purposes (Fig. 9).

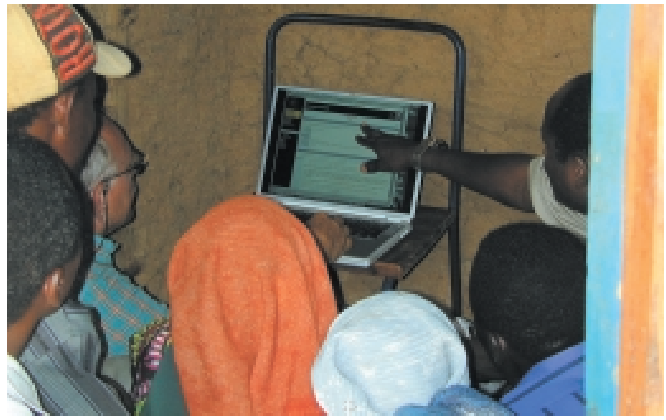


Fig. 9. The end of the Digital Divide? Querying the EcoPort database in a mud hut in rural Africa. The laptop computer holds a snapshot of the EcoPort database, which contains the equivalent of about 35 tonnes of books. The database was able to answer or provide information to more than 80% of farmers' agricultural and biodiversity questions (T. Putter, pers. comm.). Above all, it underlined the fact that the problems rural people have to solve require them having access to multi-disciplinary information managed in a manner that would give them the opportunity to validate the information and, to add indigenous knowledge for communal sharing using the Internet as medium.

In addition, there is an obvious need for baseline data. For example, rapid habitat loss in tropical forests makes their canopy inhabitants particularly vulnerable to extinction. Dissemination of scientific information to foster scientific interest in canopy organisms is crucial for the survival of canopy communities, as well as for those who study them. Sound estimates of species loss cannot be inferred from ground-based studies alone; data on the distribution and ecology of canopy organisms are essential to predict the effects of forest disturbance and fragmentation on species loss (Willott, 1999).

Unfortunately, most of the research performed in forest canopies is under-funded, particularly the organismic component of such research. As an example, we briefly discuss here the case of entomological studies. They require a sound sampling effort and then a sound taxonomic study of the specimens collected (i.e., associating specimens with formal names), based on literature, reference collections, and comparisons with type specimens. Since these are time-consuming and costly processes, entomologists often need to restrict their attention to a few focal taxa, not necessarily representative of mega-diverse insect groups (Novotny *et al.*, 2003).

Several major taxonomic initiatives have been proposed (such as the Global Taxonomy Initiative [GTI], BioNet International, Systematics Agenda 2000, All Taxa Biodiversity Inventories [ATBI], Global Biodiversity Information Facility [GBIF], All Species Inventory) which, inter alia, would build the capacity for taxonomic understanding of canopy arthropods (Cracraft, 2000). These approaches vary in their feasibility but, at this point, they remain largely unfunded. There has been widespread recognition of the crisis in staffing and available expertise in arthropod taxonomy for over a decade (e.g., Wilson, 1985) but, in general, there has been little response from government agencies and other funding bodies. More progress is being made in data basing of existing formal collections, in cataloguing already named species and in documenting available expertise. Concomitant developments in biological surveys and taxonomic expertise per se are also crucially required.

Consensus

In addition to the formal inter-governmental conventions and organizations, many organizations have been formed by scientists and others to address forest science and policy issues. While these do not directly influence international and national forest policy, they can have a vital role in synthesizing and disseminating current scientific understanding, and in formulating research agendas that foster growth of knowledge. Examples of such organizations are provided in Table 1. Some of them may be related and working in close collaboration with the bodies of international environmental conventions. Further, we introduce below at greater length six smaller scientific networks, which are specifically concerned with the study of forest canopies. Three of these networks are examples of formal physical networks of tree plots, towers and canopy cranes; two other networks represent more informal networks of scientists and the last network represents a nascent effort to mobilize the world canopy research community to address broader issues.

Table 1. Examples of scientific organizations and large networks addressing forest science and policy issues.

Organization/Network	Acronym	Mission/Focus	URL
Centre for International Forestry Research	CIFOR	International research and global knowledge institution committed to conserving forests and improving the livelihoods of people in the tropics.	www.cifor.cgiar.org
DIVERSITAS	-	International global environmental change research programme, whose missions are to promote integrative biodiversity science and to provide the scientific basis for an understanding of biodiversity loss.	www.icsu.org/diversitas
European Tropical Forest Research Network	ETFRN	Forum for communication between European organisations, researchers, EU institutions and others concerned with (sub-) tropical forest research.	www.etfrn.org/etfrn
Global Invasive Species Programme	GISP	'Partnership network' which aims to conserve biodiversity and sustain human livelihoods by minimizing the spread and impact of invasive alien species.	http://jasper.stanford.edu/gisp/home.htm
International Council for Science	ICSU	Non-governmental organization which aims to identify and address major issues of importance to science and society, by mobilising the resources and knowledge of the international scientific community.	www.icsu.org
International Geosphere-Biosphere Programme	IGBP	Scientific research programme whose mission is to deliver scientific knowledge to help human societies develop in harmony with Earth's environment.	www.igbp.kva.se
International Human Dimensions Programme on Global Environmental Change	IHDP	International, interdisciplinary and non-governmental research programme, aiming at the development and integration of research on the human dimensions of global environmental change.	www.ihdp.org
Permanent Forum on Indigenous Issues	-	To provide expert advice and recommendations on indigenous issues to the UN, and to raise awareness and promote the integration and coordination of activities related to indigenous issues within the UN system.	www.un.org/esa/socdev/pfii
International Tropical Timber Organization	ITTO	Facilitates discussion, consultation and international co-operation on issues relating to the international trade and utilization of tropical timber and the sustainable management of its resource base.	www.itto.or.jp
International Union of Biological Sciences	IUBS	Non-governmental organization whose objectives are to promote the study of biological sciences; to initiate, facilitate and coordinate research; and to ensure the discussion and dissemination of the results of cooperative research.	www.iubs.org
International Union of Forest Research Organizations	IUFRO	Non-governmental international network of forest scientists, whose objectives are to promote international cooperation in forestry and forest products research.	http://iufro.boku.ac.at
Large-Scale Biosphere-Atmosphere Experiment	LBA	International research initiative led by Brazil. LBA seeks to understand the climatological, ecological, biogeochemical, and hydrological functioning of Amazonia, the impact of land use change on these functions, and the interactions between Amazonia and the Earth system.	http://lba-ecology.gsfc.nasa.gov/lbaeco
Scientific Committee On Problems of the Environment	SCOPE	An interdisciplinary body of natural and social science expertise focused on global environmental issues, operating at the interface between scientific and decision-making instances.	www.icsu-scope.org
The Global Network for Taxonomy	BioNet-International	Dedicated to supporting sustainable development by helping developing countries to overcome the taxonomic impediment by becoming self-reliant in taxonomy.	www.bionet-intl.org
World Climate Research Programme	WCRP	International Research Programme whose objectives are to develop the fundamental scientific understanding of the physical climate system and climate processes needed to determine to what extent climate can be predicted and the extent of human influence on climate.	www.wmo.ch/web/wcrp/wcrp-home.html

Center for Tropical Forest Science (CFTS)

The Center for Tropical Forest Science (CTFS) of the Smithsonian Tropical Research Institute, in conjunction with scientific collaborators around the world, has undertaken a series of comparative, long-term studies of tropical forest diversity and change in Asia, Africa, and Latin America (http://www.ctfs.si.edu/). Using data from a global network of field sites, CTFS researchers are discovering basic biological principles that explain tropical forest dynamics, while also generating data that resolves critical forest management and conservation concerns. The central feature of the CTFS network, present at each CTFS site, is the standardized Forest Dynamics Plot. Forest Dynamics Plots are unique due to their large size and intensive sampling methods. Within each plot, every tree over one centimeter in diameter is marked, measured, plotted on a map, and identified according to species. The typical Forest Dynamics Plot is 50 hectares in size and may contain as many as 360,000 individual trees. Overall, the network plots include more than 3,000,000 individual trees representing more than 6,000 tree species, or 10% of the total tree species richness of the tropics. Utilizing the data from the standardized, intensive Forest Dynamics Plots throughout the tropics, CTFS researchers are exploring tropical forest species diversity and dynamics at a global scale. CTFS researchers also use data from the network of plots as the basis for silvicultural, socio-economic, and ecological research.

FLUXNET - Dieter Anhuf

FLUXNET was officially founded in 1997 and represents a global network of micrometeorological tower sites that use eddy covariance methods to measure the exchanges of carbon dioxide (CO_2), water vapour, and energy between the terrestrial ecosystem and the atmosphere (Baldocchi *et al.*, 2001). Briefly, the eddy covariance method is used to assess gas fluxes between the biosphere and the atmosphere. The vertical flux densities of CO_2, latent and sensible heat between vegetation and atmosphere are proportional to the average degree to which vertical wind velocity and respective measurements of CO_2, water vapour and temperature vary together. Ecologists use an opposite sign convention than meteorologists where the uptake of carbon by the biosphere is positive and this is called the NEE (Carbon Net Ecosystem Exchange).

At present, over 200 tower sites are operating on a long-term and continuous basis, although few such towers are present in Africa and India. Researchers also collect data on site vegetation, soil, hydrologic, and meteorological characteristics at the tower sites. FLUXNET's goals are to understand the mechanisms controlling the exchanges of CO_2, water vapour and energy across a spectrum of time and space scales because there is pressing need for information concerning the influence of terrestrial ecosystems and particularly of forests on biosphere-atmosphere interactions and their impact on the climate system. Specific objectives are the quantification of spatial differences in carbon dioxide and water vapour exchange rates, differing across natural ecosystems and climate gradients. Continuous measurements (every 1/2 to 1 hour) provide information on temporal dynamics (seasonal, inter-annual) to examine the influences of drought (El Niño), wet-, heat-, and cold spells. The data collected provide useful parameters to global and regional climate modelers, to determine the gain and losses of carbon from forests, to analyze the response of water and carbon fluxes to climate factors in order to predict impacts of global environmental change on forest ecosystem functions including primary production, water cycling and hydrology and to recommend management strategies for the conservation of forests. FLUXNET also provides ground information used to validate estimates of net primary productivity, evaporation, and energy absorption that are being generated by sensors on the NASA TERRA satellite. FLUXNET data available at the Oak Ridge National Laboratory Distributed Active Archive Center include monthly and

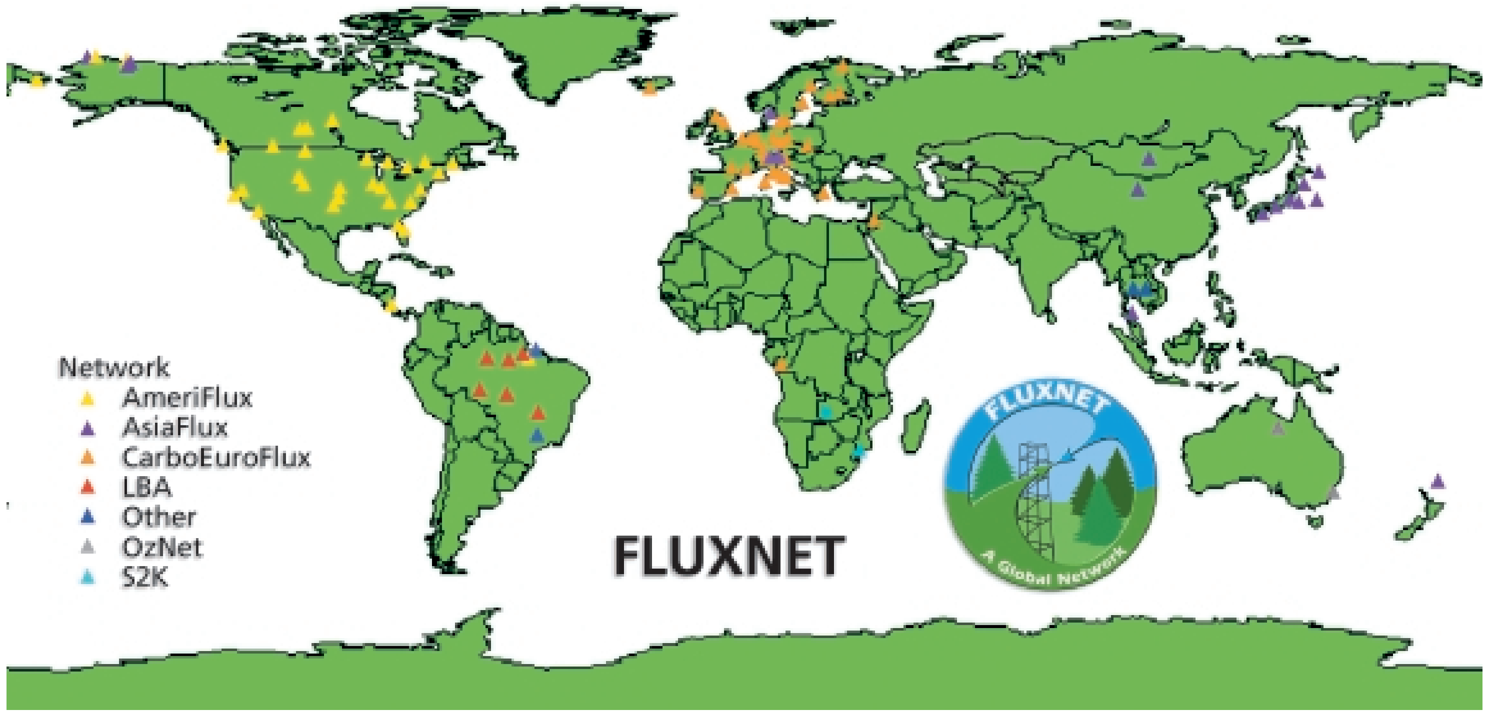


Fig. 10. Situation of the tower sites of the FLUXNET network. Modified from Baldocchi *et al.*, 2001 (Fig. 1).

annual heat, water vapour, and CO_2 flux, gap-filled flux products, ecological site data, and remote sensing products (Fig. 10, www-eosdis.ornl.gov/FLUXNET/fluxnet.html).

International Canopy Crane Network (ICCN)

The object of this publication, the ICCN was founded in 1997 (Stork *et al.*, 1997a). It represents an alliance of canopy crane sites (see next Chapter) united in a willingness to study forest canopies and to share common protocols. The network is presented at more length in Chapter 4. Its main assets and achievements are discussed in the concluding chapters of this booklet. The ICCN represents a crucial data provider that sheds light on the maintenance of complex forest processes, including canopy structure, plant phenology, local maintenance of biodiversity, biotic interactions, canopy microclimate and plant growth, and plant physiological responses to a changing environment. It could be developed into a powerful early warning system for global environmental change.

International Union of Forest Research Organizations (IUFRO) Working Group on Canopy Processes

This working group aims to promote an international forum for interactions and collaborative research for scientists working in ecology, physiology, biophysics and genetics of forest canopies (Ryan, 2002). The Canopy Process Group has been in existence for nearly twenty years and during that time it has held seven international meetings and co-sponsored two workshops. The common interest of the members of the working group is a desire to understand the physiological processes (particularly, but not exclusively, in the canopy) that regulate forest function (carbon, water, nutrient cycling and forest growth). The Canopy Processes Group provides a forum where researchers interested in canopy structure and ecophysiology can meet with researchers interested in ecosystem-level questions (http://iufro.boku.ac.at/, Unit 2.01.12).

International Canopy Network (ICAN) - Nalini Nadkarni

The International Canopy Network (ICAN) was created in 1994 to facilitate communication among individuals and institutions concerned with research, education, and conservation of organisms in tree crowns and forest canopies. Prior to ICAN's establishment, the field of canopy studies suffered from a lack of communication pathways among diverse disciplines, institutions, and individual researchers. Core activities of ICAN include maintenance of an electronic mail bulletin board, circulation of a quarterly newsletter and member directory, organization of canopy symposia, maintenance of a citations bibliographic database, and creation of instructional materials about forest canopies for children and adults.

Communication of canopy research at a global scale involves active collaboration among computer scientists and canopy ecologists to create informatics tools to provide efficient transfer of canopy-related datasets among researchers. Pilot sets of canopy data are serving to create, test, and evaluate database tools, metadata databases, and visualization programs to link datasets that relate to tree crowns and forest canopies. Increasingly, the ICAN is taking on educational and outreach projects that link directly to conservation work that is critical in forests around the world. These include consultations with the media to make engaging and scientifically accurate films, websites, and text for journalists; organizing meetings and educational 'climb-ins' for decision-makers, mainly at the regional and state level; maintaining a youth education program called 'Ask Dr. Canopy!'; and developing school curricula, targeted at middle school children. The eight-member Board of Directors is comprised of individuals who represent the various activities of the ICAN - research, education, policy-making, and conservation. The 20-member Scientific Advisory Board provides oversight and expertise in specific areas relevant to the operations. Support is provided by membership dues, donations, and grants (Nadkarni *et al.*, 1996; www.evergreen.edu/ican).

Global Canopy Programme (GCP) - Andrew Mitchell

The GCP is an outcome of the European Science Foundation (ESF) funded European Tropical Canopy Program and the ESF/National Science Foundation (USA) supported Oxford Canopy Workshop held in the UK in 1999. Participants at this workshop proposed an integrated series of studies across major environmental and management gradients to investigate the role of forest canopies in maintaining global biodiversity, global environmental conditions, and the sustainability of forests. A GCP Secretariat was formed in Oxford in 2000 with the support of the Rufford Foundation and the Maurice Laing Foundation. Since then it has established a global alliance linking organizations studying forest canopies worldwide; developed a collaborative program of research, education and conservation projects; funded a range of pilot studies and is establishing canopy training programs in Brazil and Malaysia. (Mitchell, 2001, 2002; www.globalcanopy.org). In 2002, scientists representing 14 institutions signed the Cairns Declaration on Forest Canopy Research drafted by the GCP which calls for an international program focused on forest canopies addressing biodiversity, climate change and poverty alleviation. This is posted on the Convention on Biological Diversity web site (http://www.biodiv.org/doc/ref/for-cairns-canopy-en.pdf). The GCP has also successfully introduced new language highlighting the importance of forest canopies into the Convention on Biological Diversity's Workplan on Forests approved in The Hague in 2002 (see earlier section on CBD). In Europe the European Canopy Network (EUCAN), coordinated through the GCP in Oxford, has published plans for an expanded network of European canopy cranes from Sweden, south to the Canary Islands and from Britain to the Czech Republic with the prime purpose of investigating the impact of atmospheric change on forest function in the European region. The GCP is also developing a "20:20 Vision for Forest Canopy Science" which envisages establishing a network of 20 'whole forest' observatories to investigate and monitor the impact of climate change on biodiversity from the canopy to the soil over two decades. Tropical components of this plan include suggestions for canopy cranes in Malaysia, India, Ecuador, Brazil and in West Africa. In the UK an initial canopy network of researchers has been created to plan for the introduction of a high quality canopy access facility in a UK woodland.

To date, the impact of the scientific networks described above is difficult to estimate. Some have only been established recently. Their impact may also be different whether considering the political or scientific communities, or the public at large. Undeniably, the understanding of the scaling of canopy processes has been improved in part by the proliferation of canopy sites in certain networks (e.g. FLUXNET; Ryan, 2002) and this should be a lesson for all networks concerned with spatial replication. We also note that, to date, there exists no network specifically dedicated to the study and conservation of canopy biodiversity, although the GCP stimulated discussions on this topic. The ICCN, by virtue of providing improved canopy access leading to better measurements and experiments (see next Chapter), is bound to interact with all other scientific networks presented above.

3. The study of the forest canopies

3

The study of forest canopies

Yves Basset, Vibeke Horlyck & S. Joseph Wright

The study of forest canopy is strongly associated with problems of accessing the upper canopy, often 20-60m above the forest floor. This represents a major impediment in canopy science. Many of the earlier studies of forest canopy relied upon ground-based methods, such as observation with binoculars, and there were few opportunities to study canopy organisms directly. Life-histories and population dynamics could only be inferred from such data. During the past two decades, several methods of canopy access have broadened the ability of scientists to access the canopy and have allowed the observation and collection of canopy organisms *in situ*.

Most of the means for gaining access to the canopy were developed in the tropics. A pioneering attempt to study the canopy *in situ* was by means of ladders and pulley systems, utilized during the Oxford University's expedition of 1929 in British Guiana (now Guyana) (Hingston, 1932). The few studies performed before the late 1970's used fixed systems including towers, platforms, walkways and ladders. In 1978, Perry reported the inexpensive adaptation of a single-rope technique (used by cavers to ascend vertical shafts) to the safe climbing of tall forest trees. Further, in the late 1970's, entomologists developed ground-based techniques, such as insecticide knockdown and light-trapping, to obtain mass collections of arthropods from the tropical canopy. This led to an expansion of canopy studies, augmented in the following decade with newer methods permitting access to the upper canopy, including the canopy raft and peripherals, and canopy cranes. Landscape ecologists also study the canopy with satellite remote-sensing. Below, we review briefly the advantages and limitations of each method, and discuss canopy cranes at greatest length. Canopy access is reviewed historically in Mitchell (1982), Moffett (1993), Moffett and Lowman (1995), and Sutton (2001), among others.

Fig. 11. Fogging small *Piper* trees from the ground in Papua New Guinea (photo Patrick Basset).

Ground-based techniques

Botanists and zoologists often observe plants and large canopy animals with binoculars. Further, ground-based techniques that provide indirect access to the canopy have always been popular with entomologists. The most favoured technique, insecticide knockdown ('canopy fogging', Fig. 11), includes hoisting a radio-controlled fogging or misting machine into the canopy that dispenses insecticide in different directions. Dying arthropods fall on collecting trays located just above ground level. Alternatively, one may fog or spray from the ground. Other popular ground-based methods include hoisting light traps (or other types of traps) into the canopy using pulley systems allowing convenient surveys of the traps. The main advantages of these techniques are quick implementation of a systematic and productive protocol that produces reasonably clean samples, ideal for general surveys of forest tracts and large-scale taxonomic work, as well as comparative studies. Apart from some technical limitations (e.g., dependence upon weather conditions, sampling often limited to daybreak, or night, etc.), the main disadvantages are that specimens collected are often dead or moribund, the precise origin of the specimens to a specific habitat within the canopy is unknown and often few spatial replicates are available. In addition, selective sampling of the upper canopy in tall forests is difficult, since these methods yield a mixture of specimens originating from different forest strata. The reader interested in these and other techniques used in canopy entomology may wish to consult Stork and Hammond (1997), Basset *et al.* (1997) or Adis *et al.* (1998).

Single rope technique

Perry (1978) appears to have been the first scientist to modify the single rope technique used in caving to climb tall rainforest trees. The observer climbs with harnesses and jumars on a static rope anchored at ground level (Fig. 12). The equipment is inexpensive and allows extensive spatial replication. However, beside safety and liability concerns, the mobility of the climber is often restricted, and the upper canopy or the crown periphery are often out of reach, unless climbing from taller emergent trees. In addition, the diversity of crown and canopy micro-habitats to which access may be gained is constrained by the availability of suitable branches capable of bearing the weight of climber and equipment. The method appears better suited to reach the lower parts of the canopy and as a complement to the more intensive kinds of access provided by the methods discussed below.

Fig. 12. Single rope technique in the Australian canopy (photo John Ravenscroft).

Platforms, towers and walkways

Often biologists and medical entomologists set up platforms and towers in rainforests to study insect vectors (i.e., Allee, 1926; Bates, 1944), as do meteorologists to study microclimate and gas fluxes (e.g., Baldocchi *et al.*, 2001). In particular, Haddow *et al.* (1961) launched an impressive research programme with sophisticated towers in the 1950's in Africa. These structures tend to be relatively inexpensive and may also be replaced by cheaper scaffoldings. However, their fixed access cannot be chosen at random - appropriate clearings, adjacent trees or other constraints associated with tower construction impose limitations. In addition, foliage, flowers or fruits may be difficult to reach by the observer. Using a different approach some workers have established small individual platforms in trees (Nadkarni, 1988).

Canopy walkways to conduct scientific research were first built to study ecto- and endo-parasites of mammals and herbivory (Muul & Lim, 1970; Sugden, 1982). These structures may well be affordable by research institutions and are safe (e.g., Lowman & Bouricius, 1995). They expand access to the canopy to sampling from points to transects, in contrast with platforms, towers and single-rope access (Muul & Lim, 1970). However, access to the upper canopy is difficult, since walkways, like platforms, must be supported by large, load-bearing limbs. A recent trend has been to combine platforms and walkways (Inoue *et al.*, 1995).

Canopy raft and peripherals

The Canopy Raft ('radeau des cimes' in French) is a 580m^2 platform of hexagonal shape, consisting of air-inflated beams and Aramide™ (PVC) netting. A warm-air dirigible of 7500m^3 raises the raft and positions it at specific sites upon the canopy. The raft can then be moved and repositioned as required by the dirigible. Access to the raft is provided by single rope techniques (Hallé & Blanc 1990). The Sledge ('luge des cimes' in French) is a triangular platform of about 16 m^2 which is suspended below the dirigible and which 'glides' over the canopy at low speed (Fig. 13; Lowman *et al.*, 1993). The mobility of the raft, and particularly of the sledge, is ideal to obtain spatial replicates. However, the infrastructure needed is expensive and long-term temporal replicates are difficult to obtain. Access to the foliage is mainly restricted to the periphery of the raft. Flights with the sledge are restricted to the early mornings and times of good weather.

Fig. 13. The Madagascar mission of the Canopy Raft in 2001. The dirigible moving the Canopy Sledge (photo Henri-Pierre Aberlenc).

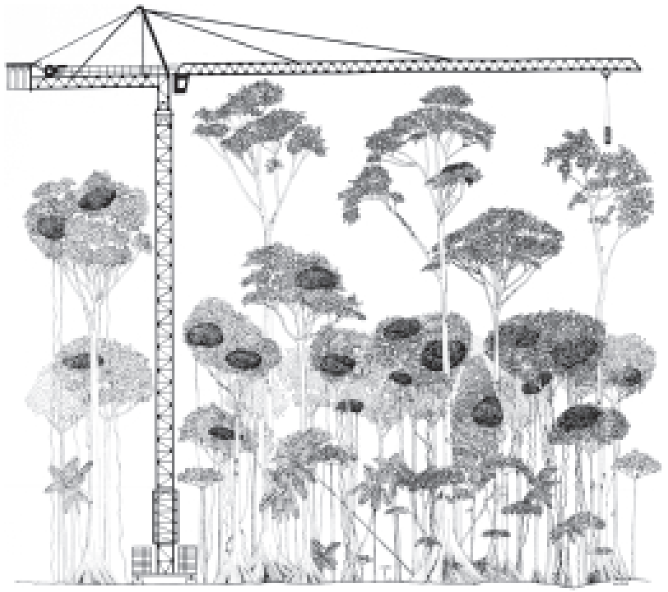


Fig. 14. Diagram showing a canopy crane in a tropical rainforest (archives of the Smithsonian Tropical Research Institute).

The Treetop Bubble ('bulle des cimes' in French) is an individual 180m^3 helium balloon of 6m in diameter which runs along a fixed line set up in the upper canopy (Hallé, 2000). The system is independent from the canopy raft and sledge although the dirigible used to move the canopy raft is used to install the transect line. The observer is seated in a harness suspended below the balloon and moves along the line with jumars. Different transects of several hundred metres have been established, but longer transects of several kilometres are planned. The equipment needed is relatively inexpensive and spatial replicates along line-transects can be easily obtained. Long-term temporal replicates along these transects could also be achieved. Possible limitations may be the relative instability of the observer due to the buoyancy of the balloon, and the difficulty to access the lower canopy. The Treetop Bubble appears to be the ideal companion method of the fixed canopy cranes, to which we now turn.

Canopy cranes

Alan P. Smith and the Smithsonian Tropical Research Institute pioneered the installation and use of a construction tower crane to gain access to the canopy in a tropical forest in Panama (Fig. 14; Wright & Colley, 1994, 1996). This was realised in 1990 in collaboration with the United Nations Environment Programme (UNEP), with funding provided by the governments of Belgium, Denmark, Finland, Germany and Norway through UNEP's Clearing House Mechanism and by the Smithsonian National Board of Associates for the purchase and installation of the construction crane. The construction crane as a research tool was so successful that a permanent crane was installed in 1992 in Panama, followed by a second in 1997 (Fig. 15). Since then, other cranes have been established in a variety of temperate and tropical forests (Chapter 4; Parker *et al.*, 1992; Wright, 1995; Stork *et al.*, 1997a).

Fig. 15. The San Lorenzo canopy crane in Panama (photo Marcos Guerra).

A metal basket called the gondola (Fig. 16), in which observers stand, is hoisted above the forest by the crane and lowered to research locations within the canopy. Since gondolas and cranes are standard equipment in the construction industry, no modifications are necessary to adapt this equipment for scientific purposes. Canopy cranes enable easy and safe three-dimensional access to the canopy. The gondola may be lowered into gaps, all the way to the ground, or into the crown of large open trees. The crane facilitates access to the whole forest column within reach of the crane. Heavy equipment can be carried onboard the gondola, and some cranes have power outlets in the gondola for electrical equipment. Movement of the crane and gondola is controlled either through radio communication with the crane operator or by remote control operated from the gondola. A canopy crane may be installed with minimal impact on the forest, with either a helicopter or a mobile crane. An existing gap in the forest may serve as a potential crane site.

Fig. 16. Connecting the crane hook to the gondola at Parque Natural Metropolitano in Panama (photo Marcos Guerra).

The main advantages of canopy cranes are the safety and excellent access within much of the canopy (less so in the lower part), the possibility of obtaining many temporal replicates, and the ability to lift heavy equipment into the canopy rapidly (Fig. 17). Easy and non-destructive access to the upper canopy are particularly useful for measuring photosynthesis in situ, which can be measured on a single leaf or with the help of dataloggers that can be installed to record measurements continuously. Behavioural observations of animals foraging in the upper canopy may be made routinely. In particular studies of canopy insects, observations on their feeding behaviour and life cycles are easily performed in the upper canopy with canopy cranes. However, problems related to pseudoreplication at the meso-scale are patent within the relatively small and fixed crane perimeter (seldom exceeding 1ha in area), and the costs of purchasing, erecting and maintaining a crane are high, particularly in remote tropical locations. Crane use may also be restricted during stormy or windy weather.

To conclude, the limitations of each method of access to the canopy are obvious. There is no doubt that the choice of mode of access and sampling methods must be tailored to the particular scientific questions being posed. This multi-faceted approach calls for (1) increasing collaborative effort (see preceding chapter); and (2) the use of multiple and complimentary techniques to create, for example, a ‘canopy station’ (e.g., A. W. Mitchell, cited in Lowman *et al.*, 1995; Hallé *et al.*, 2000; Mitchell, 2001). This would permit a combination of methods to provide detailed access (cranes, canopy raft), temporal replication (cranes, towers, walkways) as well as spatial replication (single rope technique, canopy sledge, treetop bubble). The more ‘mobile’ methods (single rope technique, sledge, treetop bubble) could be used to assess whether samples and observations obtained with ‘fixed’ methods (towers, walkways, cranes) are representative. One may also imagine merging different methods of access to the canopy and sampling, such as, for example, entomologists performing insecticide knockdown with the canopy sledge. Ideally, in order to reduce costs, these ‘canopy stations’ could be developed at existing crane or towers sites.

Fig. 17. Measuring leaf uptake of reactive nitrogen, Jed and Kimberlee Sparks, researchers from Cornell University, make leaf-level measurements of photosynthesis and reactive nitrogen uptake from the San Lorenzo crane in Panama (see Chapter 4.3.5). From the gondola, large amounts of equipment including compressed gas cylinders, a photosynthesis system and a device for measuring trace amounts of gaseous reactive nitrogen can be easily moved to multiple points within the canopy (photo Marcos Guerra).

4. The International Canopy Crane Network

4 The International Canopy Crane Network

4.1. Preamble

Yves Basset, Vibeke Horlyck, S. Joseph Wright & Nigel E. Stork

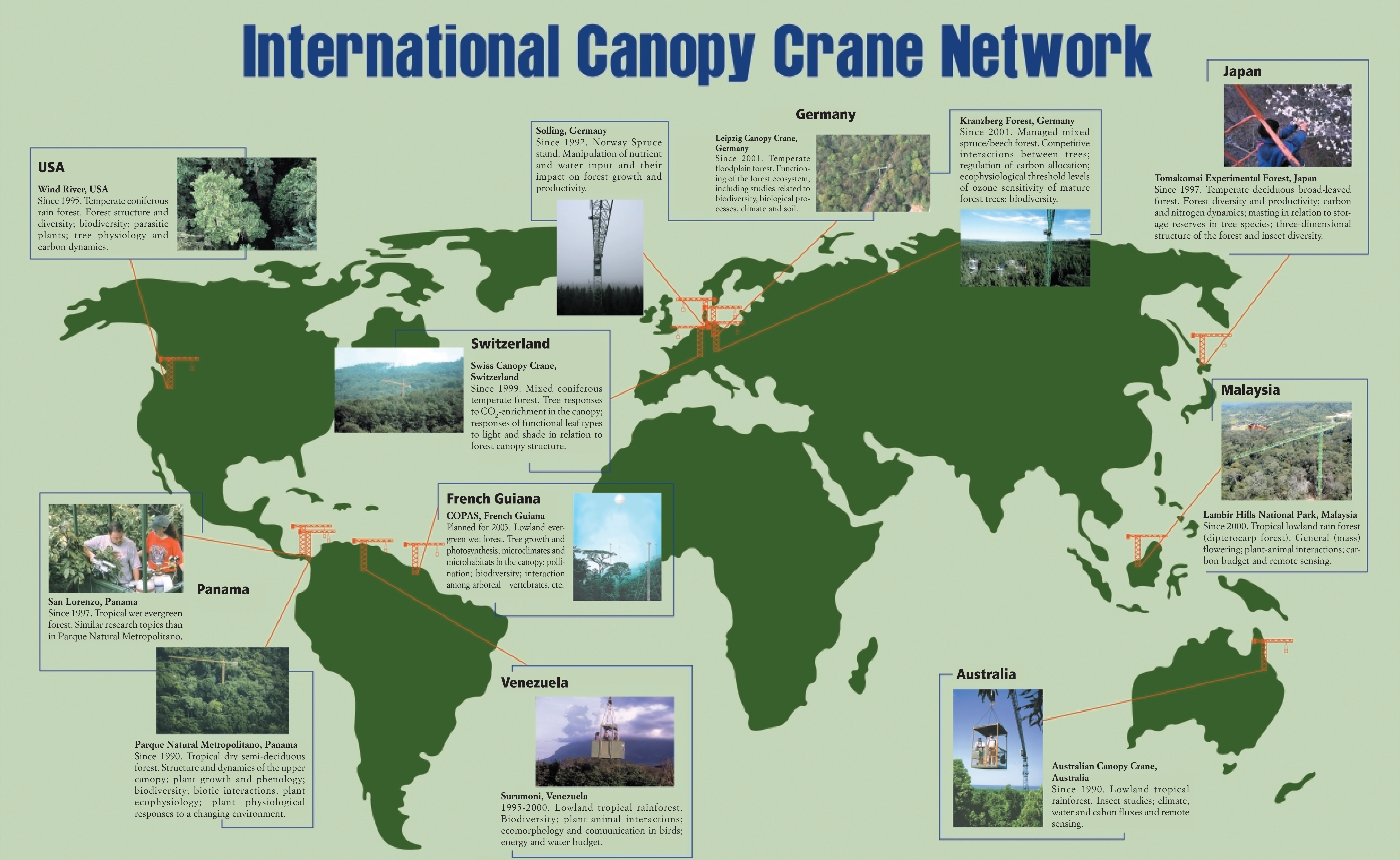
Many of the important scientific questions in understanding tropical and temperate forests and practical problems in managing these ecosystems require an understanding of the least known layers, the forest canopy. Inevitably, over the last 30 years a number of biologists have had to become canopy specialists in order to address widespread and far reaching issues such as forest fragmentation, extinction, water use, climate change and the distribution of global biodiversity. One recurrent problem these canopy scientists all face is the difficulty in obtaining enough spatially independent replicates to allow robust statistical analyses because of problems in gaining canopy access. Often, it leads to 'pseudoreplication' (Hurlbert, 1984) within the sampling universe and to disturbance and possible interference with the object being studied (Barker & Pinard, 2001). In statistical terms, when two or more supposed replicates are too close to each other they are considered not to be fully independent of each other and are therefore pseudoreplicates. Comparing data sets from different biogeographical regions may improve replication and may help to explore whether community patterns hold at different spatial scales and in different forest biomes.

The International Canopy Crane Network represents an answer to these problems. By replicating experiments in different forest types, data held collectively by the network have more statistical power and the generality of hypotheses can be tested in a variety of situations. The network represents a collaboration between eleven canopy crane sites. The main objective is to promote collaborative research on the forest canopy and to exchange students and scientists among the sites. The end product of the network is envisioned as a standardized, long-term monitoring of forest canopies, which should supply a wealth of data on the structure, biodiversity and function of forest canopies.

A second goal is to increase the dissemination of data and results resulting from canopy studies to policymakers, governments and organisations involved in multilateral negotiations, via the International Canopy Network (Chapter 2). Collaboration and comparative studies among the crane sites will be facilitated by implementing hierarchical research protocols for collecting baseline data such as on forest structure, arthropod diversity, and general plant physiology. Certain fields for future collaborative research have already been identified (see Chapter 6).

The first canopy crane was erected in a dry tropical forest in Panama in 1990 under the auspices of the Smithsonian Tropical Research Institute (STRI), the United Nations Environment Programme (UNEP), and the Parque Natural Metropolitano, Panama. This first crane attracted considerable interest from scientists and was instrumental in generating an array of studies published in leading scientific journals (see Chapter 4.3.5). In 1992, the University of Göttingen established a crane in a temperate forest at the Solling research station in Germany. In April 1995 a crane was erected in a temperate forest of Washington State, USA, by the University of Washington. In November of the same year the Austrian Academy of Science established a crane in the Amazonian lowland forest of southern Venezuela. STRI installed a second crane, funded by the Government of Denmark, in a wet forest in Panama in May 1997. Another crane was erected in November 1997 in the Tomakomai Experimental Forest on Hokkaido, with funds from the Japanese Government. One year later, the Australian Canopy crane was established in Queensland, followed by the Swiss Canopy crane (Basel) in 1999. In April 2000, a crane was further installed in Sarawak, Malaysia, with funding from the

International Canopy Crane Network



USA

Wind River, USA
Since 1995. Temperate coniferous rain forest. Forest structure and diversity; biodiversity; parasitic plants; tree physiology and carbon dynamics.

Germany

Solling, Germany
Since 1992. Norway Spruce stand. Manipulation of nutrient and water input and their impact on forest growth and productivity.

Leipzig Canopy Crane, Germany
Since 2001. Temperate floodplain forest. Functioning of the forest ecosystem, including studies related to biodiversity, biological processes, climate and soil.

Kranzberg Forest, Germany
Since 2001. Managed mixed spruce/beech forest. Competitive interactions between trees; regulation of carbon allocation; ecophysiological threshold levels of ozone sensitivity of mature forest trees; biodiversity.

Japan

Tomakomai Experimental Forest, Japan
Since 1997. Temperate deciduous broad-leaved forest. Forest diversity and productivity; carbon and nitrogen dynamics; masting in relation to storage reserves in tree species; three-dimensional structure of the forest and insect diversity.

Switzerland

Swiss Canopy Crane, Switzerland
Since 1999. Mixed coniferous temperate forest. Tree responses to CO_2-enrichment in the canopy; responses of functional leaf types to light and shade in relation to forest canopy structure.

Malaysia

Lambir Hills National Park, Malaysia
Since 2000. Tropical lowland rain forest (dipterocarp forest). General (mass) flowering; plant-animal interactions; carbon budget and remote sensing.

Panama

San Lorenzo, Panama
Since 1997. Tropical wet evergreen forest. Similar research topics than in Parque Natural Metropolitano.

Parque Natural Metropolitano, Panama
Since 1990. Tropical dry semi-deciduous forest. Structure and dynamics of the upper canopy; plant growth and phenology; biodiversity; biotic interactions, plant ecophysiology; plant physiological responses to a changing environment.

French Guiana

COPAS, French Guiana
Planned for 2003. Lowland evergreen wet forest. Tree growth and photosynthesis; microclimates and microhabitats in the canopy; pollination; biodiversity; interaction among arboreal vertebrates, etc.

Venezuela

Surumoni, Venezuela
1995-2000. Lowland tropical rainforest. Biodiversity; plant-animal interactions; ecomorphology and comuunication in birds; energy and water budget.

Australia

Australian Canopy Crane, Australia
Since 1990. Lowland tropical rainforest. Insect studies; climate, water and cabon fluxes and remote sensing.

Fig. 18. The 12 sites currently part of the International Canopy Crane Network, with an indication of the first year in operation, forest type and main research topics.

Japanese Government. Eventually, in 2001, two new cranes were erected in temperate forests of Germany, in Leipzig and Freising, respectively.

The network now consists of six cranes erected in temperate forests and five in tropical forests (Fig. 18). They will be shortly joined by the Canopy Operation Permanent Access System (COPAS) in French Guiana, a fixed device with a different conception (Chapter 4.3.2). These sites are located in forests from different types, biomes and biogeographical regions, such as northern coniferous forest, mixed temperate forest, decidous broad leaf forest, tropical dry lowland forest, and tropical wet lowland forest. To date, no crane site has been established in Africa.

The International Canopy Crane Network was founded in 1997 (Stork *et al.*, 1997a), during the organisation of a Tropical Forest Canopy Symposium held in Panama in March 1997, and in response to an earlier call to promote the long-term studies of forest canopies (Parker *et al.*, 1993). Sixty-one participants representing 23 nations attended the meeting in Panama, including delegates from UNEP, UNESCO, CIFOR, and IUCN. This meeting complemented a series of International Canopy Conferences held in Sarasota, USA, in 1994 and 1998; and in Cairns, Australia, in 2002, with the next meeting planned for Leipzig, Germany, in 2005.

Each crane site has unique peculiarities and its associates are involved in different research topics. Yet some baseline investigations are common to all sites: identifications of plant and animals present, mapping and measurement of trees, microclimatic studies, etc. The 'Global Canopy Handbook', edited by the Global Canopy Programme (Mitchell *et al.*, 2002), presented the different crane sites of the network, particularly in terms of technical characteristics and costs of installations. In the following sections, the manager(s) of each crane research facility were asked to describe the climate and vegetation of their site and to provide an overview of the past, present and future research at their facility. These findings are further summarized in Chapter 5 and put into the perspective of global canopy research.

4.2. Cranes in temperate forests

4.2.1. Basel, Switzerland

Christian Körner and Gerhard Zotz

Fig. 19. View from the forest floor to the top of the crane, which was set up in a small natural gap of a few m^2.

Background

The Swiss Canopy Crane (SCC, Fig. 19 and Table 2) was erected with the help of a helicopter in March 1999 at Hofstetten, close to the town of Basel. It is managed by the Institute of Botany, University of Basel, and is sponsored by the Swiss Federal Office of the Environment (BUWAL), the Swiss National Science Foundation (SNF), and the University of Basel. On the fenced research site (*circa* 1ha), there is a field laboratory, power and telephone line. In September 2000 a large-scale canopy enrichment system (web-FACE: Free Air CO_2 Enrichment) was installed, which permitted exposure of 14 adult trees to elevated levels of carbon dioxide (CO_2; a detailed description of this system can be found in Pepin & Körner, 2002).

Table 2. Site and crane characteristics of the Swiss Canopy Crane.

Variables	Characteristics
Location	Hofstetten, 12 km south of the city of Basel in NW Switzerland 47°28' N, 7°30'E
Altitude	550m
Mean annual air temperature	10°C
Mean annual rainfall	990mm
Type of forest	Mixed coniferous temperate forest
Area of forest accessed by the crane	0.28ha (note: the crane is located in a very small natural gap)
Canopy height	32-38m
Crane model	Liebherr 30LC, fixed
Height of tower / Length of jib	45m/30m
Maximum height reached by the gondola	37m
Gondola type	a: Cylindrical, model RM1-300A/32; 65cm in diameter b: Square, model SEC 02/600; 1.2 x 1.2m
Number of persons carried by the gondola	a: 1 person b: 4 persons
In operation since	1999
Main research topics	• Tree responses to CO_2-enrichment in the canopy • Responses of functional leaf types to light and shade in relation to forest canopy structure
Remarks	Fenced research site, equipped with laboratory, power and telephone lines
Management	Institute of Botany, University of Basel
Contacts	Prof. Christian Körner, University of Basel, Ch.Koerner@unibas.ch Dr Gerhard Zotz, University of Basel, gerhard.zotz@unibas.ch
Web site	www.unibas.ch/botschoen/scc/
List of publications	www.unibas.ch/botschoen/scc/
Fees for researchers	Negotiable on a case to case basis

The SCC is administered by the Institute of Botany, University of Basel. Three technicians ensure day-to-day operation of the crane, the web-FACE system and the monitoring of macroclimatic and microclimatic variables. The crane site was primarily selected to allow comparative studies of the impact of elevated CO_2 on mature individuals of typical European forest tree species. In addition to questions related to global change, the high tree species diversity at the site provides a unique opportunity to study various other topics in plant sciences, entomology, or forest pathology (Hoch *et al.*, 2003).