Could there be scientific parameters, e.g. energy (or entropy!) to make an objective assessment? Thinkers and seers have enlightened us through the ages; however, we may plan a systematic investigation utilizing modern science to understand these questions.

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Canopy science and its relevance in India

M. S. Devy and T. Ganesh

Tropical forest canopies are the least explored regions in the world. The estimate on global species richness was drastically revised after a short exploration of forest canopies. Yet, it still remains one of the least understood regions in our biosphere. Many brave researchers in the past have explored these regions with limited accessing capabilities across the globe and have revealed interesting findings on the behaviour of plants and animals. In recent times canopy science, thanks to hi-tech accessibility, is emerging as a new discipline where more interdisciplinary and large-scale research possibilities are forthcoming; canopy–atmosphere interactions, structural and functional aspects of canopy on biodiversity are a few among them. Forest canopy research can also provide inputs to many global-level processes such as climate change. Here, we review the direction that canopy science has taken in recent times in the tropics and also explore the possibilities of pursuing canopy science more intensively in India.

To reach into the rainforest roof is not an easy task, either for man or the giant trees which give birth to small offspring.

– Mitchell[1]

Global scenario

The canopies of tropical forests are unique in many aspects with diverse habitats, of which we know very little. These have been recognized as the last biotic frontier and the heart of biodiversity[2]. Much of the biodiversity found in tropical forests is in the canopies. Terry Erwin[3], who estimated insect diversity in the canopy through fogging experiments in Central America, revised the estimate of insect species numbers from 5 to 30 million. This has brought the canopy into the limelight of science and has kindled interest in other parts of the world. Canopy studies in the past and in most parts of the world were hampered by lack of adequate safe-climbing gears to access the rainforest roof. However, this did not hamper the spirits of some pioneering workers in the canopies.

Canopy research started with an initial curiosity of researchers to access and discover what is there in the treetops. A few dedicated researchers operating on shoestring budgets in various parts of the remote tropics have come up with some interesting discoveries from the canopies and have highlighted how little we know about these 'last frontiers'. Elliot McClure[4] went up a ladder in Malaysia to realize the importance of periodic flowering and fruiting for the canopy-dwelling animal community. Chan and Appanah[5] revealed for the first time how minute thrips are important pollinators of towering Dipterocarp trees in Malaysia. Nadkarni[6,7] and her colleagues in Costa Rica used Single Rope Technique to demonstrate that canopy trees actually put forth adventitious roots that run below thick mats of accumulated organic matter on the branches in which they support epiphytes to supplement their nutrition. After a decade of work in the canopy, Lowman[8] pointed to the previous gross underestimation in herbivory by ground-level workers and estimated longevity of canopy leaf to span across 4–10 years. Such exciting findings are from *in situ* work of people who have overcome the obstacles of gravitation.

In recent times a range of high-tech equipments such as walkways, cranes, balloons and airships are used to access the canopy. With the commissioning of better access systems both in temperate and tropical sites around the world, a wide range of studies from biodiversity assessment to ecological processes have emerged from many sites[9]. In Asia, Inoue and Ahmid[10] initiated a canopy programme at Lambir in Sarawak. It was an integrated approach to canopy research involving numerous researchers on various aspects, including plant–animal interactions, monitoring of physical environment, and ecophysiology. They used towers with interconnected walkways for accessing the canopies.

Emerging into a distinct discipline

Canopy science is now emerging as a recognized field and is slowly evolving as a distinct discipline. Some aspects of canopy research now involve multiple researchers approaching a common question from various dimensions and trying to use more harmonized methods and cross-site analysis[11]. One example is the estimation of biodiversity of canopy arthropod from both old and new world tropics[3,12–14]. Similarly, a community-wide survey of pollination modes has also emerged as a key topic. Canopy studies have facilitated pan-tropical comparisons of pollination modes of trees to address evolutionary questions such as why are community pollination processes different between sites and what are the biotic and abiotic factors that drive these processes[15–17].

Forest canopies are not just an abode for biologists, but many meteorologists have also been contributing to 'canopy science'[18]. Forest canopies are at the interface between forests and the atmosphere. Many important forest–atmosphere interactions such as photosynthesis, respiration, carbon flux, and water and nutrient cycling take place in this region. On a global level, we need to know how plant–atmosphere interactions are likely to be affected by the changing global process. Changes in plant–atmosphere interactions can have cascading effects on animals which interact with plants as well as with the atmosphere. In recent times, such issues have gained momentum especially in the present context of global climate change. For instance, increasing atmospheric CO_2 is likely to affect rates of herbivory. Increased levels of herbivory will have consequences on forest productivity[19]. Studies are underway to address these issues in temperate condition, but we need studies from tropical regions which experience high levels of herbivory. The process of carbon sequestration, which is of major international interest, has rarely been examined at the leaf level in forest canopies. Extrapolation has been carried out by scaling-up of gas flux models from the leaf to stand to regional and global scales. Unfortunately, such models are based on remarkably little hard evidence.

The latest entrants to the field are remote sensing (RS) and GIS experts. They suggest that a library of hyperspectral signatures of various tree species using the canopy access systems, when integrated with high-resolution satellite imageries such as ICKNOS, will aid in working out the exact spatial distribution of desired tree species[20]. This will perhaps enable us to ask questions with regard to spatial turnover of species composition over a large scale, unimaginable by actual ground work in terms of time and labour. This can have important applications for conservation and bio-prospecting. RS and GIS experts can help determine canopy structure across a large spatial scale. Measurements of canopy structure are particularly important because structure is a guide to its function. Structure is also a convenient means for comparing stands. Structure can help in comparing canopies of the world and develop new perspectives on how canopies have evolved. Making a set of standardized measurements of canopy structure at major canopy-research sites using space-based LIDAR has become the basis of global comparison among forests[21]. The data can actually be transformed and analysed to provide three-dimensional representations of the structure of each canopy for statistical and visual comparisons between stands.

The influence of canopy structure on micro-climate, energy partitioning and transport has mainly been drawn on average description of the structure from various regions, and there exist no empirical data from the tropics. Even the influence of canopy structure on arboreal mammals across the tropics is based on average conditions[22]. However, it is also recognized that influence of structure is site-specific. It would be interesting to examine how abiotic and biotic factors are linked to structure of the canopy. How much do structural differences contribute to micro-climatic differences, say, between stands? Does it influence the phenology of the tree species and thereby animal community? Perhaps, subtle differences in stand phenology within a forest type could actually be linked with the ranging behaviour of many arboreal communities that we observe. A collaborative effort of climatalogists and biologists will help advance this important component of canopy science.

Tropical canopy biologists are at the threshold of exploring a new frontier, with new perspectives and newer approaches. We have the opportunity to address some fundamental questions concerning biodiversity such as: Does the distribution of canopy-dwelling species match those near the ground across large spatial and temporal scales? What is the role of canopies of different structures in canopy–atmosphere interactions? What is the level of productivity, carbon sequestration across spatial scales or more simply, does one forest canopy sequester more carbon than other types within tropical regions? Canopy understorey interactions are also not clearly understood. Does herbivory reduce the productivity of the trees in the tropics or does it actually promote nutrient cycling? Many such questions will be addressed in the next few years, as canopy science becomes a more integrated discipline and does not remain only a biologist's last frontier.

A growing number of canopy biologists share their experiences and findings in the International Canopy Conference held once in four years. Recently, the Third International Conference was held at Cairns, Australia. Apart from this, sessions on canopy biology figure in some major symposia like those held by the Association for Tropical Biology. The first comprehensive book on canopies edited by two renowned canopy biologists, Meg Lowman and Nalini Nadkarni[11], was published in 1995 and has become a benchmark for future canopy research. This was followed by the *Global Canopy Handbook* published by Global Canopy Programme, which gives a complete compilation of various methods used by many researchers and also updates the recent developments in the field[9]. Although there is no journal dealing completely with canopy science, *Selbyana*, brought out by Selby Botanical Gardens at Florida carries a large number of articles on canopy work. Apart from these, the International Canopy Network (ICAN) has played a pivotal role in building an interdisciplinary and international communication network of canopy scientists and other interested people. Global Canopy Programme (GCP), a relatively newer body aims at integrating forest studies across the world, especially on issues relating to biodiversity, ecosystem dynamics and climate, apart from the goods and services they offer. GCP also aims at disseminating the results to various users and stakeholders, including policy makers. GCP, more recently, has lobbied for greater emphasis on canopy component in the Biodiversity Convention. One of its agenda is to raise funds from various sources and disperse funds to projects which fall into the core area identified by them[9].

The need for canopy programme in India

Biodiversity locked up in the canopy can be exceedingly large, as much as 50% or more of an ecological community[2,23]. India is recognized as a mega-diversity country with two hot spots of biodiversity, the Western Ghats and the NE Himalayas[24]. Yet almost all the biodiversity assessments have been conducted at the ground level. The first attempt to ascend the canopy in India for scientific work was made in the wet forest trees of the Kalakad Mundanthurai Tiger Reserve in 1994, for initiating a study on the canopy trees pollinated by social bees[25] (Figure 1). This was followed by community-level exploration of pollination modes of 80-odd species for over eight years[17]. This makes Kalakad one among the three sites where a large-scale community-level pollination work has been attempted[15–17]. Based on some interesting findings of the earlier work on *Cullenia exarillata*, a keystone species for arboreal mammal community[26], Devy and Ganesh are now pursuing a more intense study of this interaction by setting camera traps in the canopy. Apart from this, a long-term phenological study on leaf-flushing, flowering and fruiting of canopy trees is in progress at the same site (T. Ganesh, unpublished). Phenological study showed that a good number of species flower after prolonged intervals of five or even more number of years. Study on the seed predation by arboreal mammals showed that predation ranged from 1 to over 90%. Work is in progress to examine how canopy processes such as phenology and seed predation have a bearing on the structure of the tree species in the forest.

Figure 1.

However, much more remains to be examined in the canopy of the Indian forests. Our biodiversity could get a fresh estimate if we begin to document the lesser known taxa in the canopy. The recently launched National Biodiversity Strategy and Action Plan (NBSAP) in India is attempting to include biodiversity-related information including distribution of endemic and endangered species of various taxa and site-specific threats and pressures at regional level for strategic planning for biodiversity conservation[27]. It has also emphasized the need to explore new frontiers and not merely linger on charismatic species approach. Time is now appropriate to initiate a programme to investigate this 'unexplored biosphere' in India, to strengthen this move. The biodiversity assessments of canopy require a constellation of experts dealing with various taxa, especially from lesser-known groups.

Processes such as plant–animal interactions, canopy–understorey interactions, canopy–atmosphere interactions are also vital areas of research. Forest canopies are an important component of the surface that control climate from a local to global scale being a significant sink of carbon and a source of water vapour[28]. Most canopy micro-climatic models which exist today, are generally based on average conditions[18]. However, Anhuf[29], has recently pointed out that site variations can occur because of differences in forest structure, composition and ecological function. There are on-going studies on the effect of global climate change on various forest types in India and its consequences on biodiversity[30]. It will be interesting to integrate this with the forest canopy study, which could yield meaningful results for the Indian region. Nadkarni and Rodrigo[31] had demonstrated the canopy epiphytic community in montane forests of Monteverde as an effective biotic tool for detecting the global climate change. Perhaps, our canopy may also harbour such indicators that remain to be identified.

Awareness and education

Ecosystem goods (such as food) and services (such as interception of water and pollination) are benefits that human populations derive, directly or indirectly, from the canopy. However, outside the scientific community, there are few who can understand this and a need to generate awareness about canopies is essential for forest conservation. The canopy-access systems, once established, can be a versatile tool to generate this awareness. Similarly, canopy access in reserve forests with lesser protection status could also be used for eco-tourism in a restricted form, to complement the dearth of funds. Part of the funds could be directed to the welfare schemes of forest-dependent communities. As most children love to climb trees, the canopy with absolute safety standards, would be an ideal place to deliver conservation education programmes. This can captivate children and perhaps leave a long-term impact on biodiversity conservation.

Conservation importance

Forest canopy studies can provide compelling reasons backed by scientific data to encourage conservation of our forests. It will not only highlight how diverse our canopies are, but also how significantly they contribute to the global-change processes such as climate change. Canopies buffer the earth surface from the vagaries of extreme weather patterns, and conservation of canopy surface can have a significant effect on soil and water conservation. Canopy research can give useful inputs to forest and other related departments which can use the knowledge to protect and enhance biodiversity conservation in their region. As mentioned earlier, canopies can be a wonderful place to deliver any conservation message and build a lasting impression of forests on young minds.

To sum it all, canopy science, like space science, can take us to the 'unknown' and there might be exciting possibilities which are hard to visualize from ground-based observations and imagination.

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