The Diversity of Tropical Insect Herbivores: An Approach to Collaborative International Research in Papua New Guinea

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Abstract: *Arthropods represent a large proportion of biodiversity on earth. In particular, insect herbivores are extremely diverse in tropical rain forests. How can we cope with the processing of the countless insect specimens collected in species-rich habitats, such as tropical rain forests? The approach we have taken is to train local people (parabiologists) to master basics of insect collecting, mounting and sorting, digital photography and to work with simple but yet powerful computer databases. Sampling and processing protocols integrate low-cost collecting methods, training and computer technology. Merits and rewards of intense parabiologist training are discussed with regard to the performance of ecological research projects in the tropics. We attribute the success of our approach to (a) the local knowledge, manpower available and willingness to study the environment, particularly via modern computer techniques; (b) recent developments in computer hardware (e.g., speed and mass storage), which made digital photography a useful, relatively low cost tool; and (c) higher data quality due to the increased number of replicates and side experiments performed by the parabiologists. Routine training of local parabiologists could have deep implications for the conservation and management of tropical rain forests, in boosting scientific knowledge of food webs in rain forests, and in promoting environmental awareness and interest in non-timber products in local communities. Our international research group studying the diversity of tropical insect herbivores, centered at the Bishop Museum, Honolulu, has implemented a series of projects in Papua New Guinea since 1987. More recently, we have initiated a series of parallel projects in Guyana. To date, about 140,000 insect specimens have been collected and processed in the various projects. The research group has produced over 40 ecological and taxonomic publications and many more exciting data are yet to be fully analysed and reported. Over the years, the group has relied increasingly on the training of local insect parabiologists, to improve the collection and processing of specimens, but also to set up various experiments and to record additional ecological variables to help in the interpretation of the results. This approach has been particularly successful in Papua New Guinea and has allowed the group to reduce drastically the lag time between initial sampling and publication (both in journals and on the World Wide Web), with a concomitant improvement in data quality. For more information, see http://www.bishop.hawaii.org/bishop/natsci/ng/ngecol.html.*

1. Introduction: Challenges in the Study of Rainforest Insects

Rainforest insects exhibit extraordinary species diversity This is a prime reason for as well as a prime obstacle to their study. Estimation of global species richness of tropical insects continues to be a subject of intense debate (see Basset et al. 1996a for a recent summary of discussion sparked by Erwin 1982). But more importantly, ecological and taxonomic research in rainforest ecosystems is needed to understand the factors generating and maintaining this diversity. The initial, and crucial, step in every such investigation is to catalogue species composition and abundance of organisms in the system under the study.

A typical quantitative sample of insect herbivores from rainforest vegetation contains a large number of species. A significant proportion of these species, often as high as 60%, are rare, represented by only single specimens (e.g., Allison et al., 1997; Basset and Kitching, 1991; Morse et al., 1988; Novotny, 1993; Robinson and Tuck, 1996). Such abundance distribution indicates insufficient sample size for most practical purposes, as (i) a large number of singleton species means that there is probably a substantial number of species which were not collected at all, and (ii) any inference on their biology from their distribution in the samples is impossible for singletons and other rare species.

The fragmentary nature of our knowledge, lacking a universal taxonomic framework for storage and cross-referencing information between research projects (Janzen, 1993), is one of the principal causes of slow progress in the study of such theoretically and practically important areas as host specificity and species richness of tropical herbivores (Basset, 1992; Gaston, 1993). Cross-referencing morphospecies between samples becomes progressively more time-consuming with increasing sample size, as the number of morphospecies in the samples becomes very high. Studies on rainforest trees in particular have to deal with enormous species richness of insects. For instance, about 1,200 species of beetles was collected from 19 trees of a single species in Panama (Erwin, 1982), approximately 3,000 insect species from 10 trees belonging to 5 species in Borneo (Stork, 1987), 759 insect species from a single tree species in Australia (Basset and Kitching 1991), 418 species of beetles from a tree species in New Guinea (Allison et al., 1997) and 792 herbivorous species of insects from 15 species of *Ficus* in New Guinea (Basset and Novotny, MS). In addition to reference collections of voucher specimens, computer databases and identification keys, tailored to the specific needs of each project, can become powerful tools in the processing of samples (Basset et al., MS). Recent progress in computer technology made such databases, using digital images of species, widely accessible.

Long-term studies in the tropics have shown the importance of seasonal factors and spatial heterogeneity in affecting insect communities (e.g., Janzen, 1974; Wolda, 1988). Any representative sample from a rainforest community thus must involve numerous spatial and seasonal replicates. For instance, a minimum of 100 to 300 collecting days was needed to characterize leaf chewing herbivores on a tree species in montane rainforest in New Guinea (Basset, 1996); a full year of collecting from more than 1,000 trees was not sufficient for exhaustive sampling of herbivores feeding on 15 *Ficus* species in a lowland rainforest (Basset and Novotny, MS). Similarly, a very large sampling effort scattered throughout several years was needed to describe herbivores feeding on *Piper* spp. (Marquis, 1991). Unfortunately, there is no *a posteriori* remedy to insufficient sampling; for instance, total species richness can be estimated from partial samples, but all extrapolation methods perform poorly if samples are insufficient (Colwell and Coddington, 1994).

In summary, high numbers of species, often with no formal taxonomic descriptions and knowledge on their biology, together with large spatial and seasonal variability in the distribution of insects, are major challenges in the study of rainforest insects. In this contribution we suggest that these challenges can be met with the help of parabiologists, i.e. local people trained to master basics of insect collecting and mounting, experimentation with live insects and sorting of insects into morphospecies with the help of digital photography and simple but yet powerful computer databases. As our studies of insect herbivores in Papua New Guinea show, *this approach allows production of high-quality* insect data and material available for subsequent taxonomic studies.

2. Moth Community Surveys in Papua New Guinea: A Biodiversity Assessment Tool

Work in the Indo-Australian region (Holloway, 1976, 1984) has demonstrated the potential of using moths as biodiversity indicators. Over past three years we have been exploring that potential in PNG. We employ portable generators to power 250 watt mercury vapor and 15 watt ultraviolet lights which illuminate several white cloth sheets, usually set up on ridges overlooking the forest. Moths attracted to the sheets are randomly collected as they settle, killed and packaged. All specimens are subsequently sorted into morphospecies. From these data, we calculate an *alpha* biodiversity index as the overall assessment of the moth community, as this appears to be the most useful measure for such samples (Taylor et al., 1976).

As with other rainforest insect studies, the number of specimens needed to make up useful sample sizes for these studies is considerable. Calculating *alpha* for increasing cumulative sample sizes over a series of nights in Southern New Ireland, the index was affected heavily by sample size, when it comprised less than about 2,500 specimens (Orsak et al., 1975). This results in huge numbers of specimens that must be collected and sorted. For example, a single expedition produced 43,400 specimens in about 230 hours of light trapping. Processing such large samples potentially requires enormous amounts of high-priced time, which could render the process uneconomical. Our work with parabiologists have proven critical to making the asssessments economical, rather than prohibitive. In fact, their participation and skills has provided many spin-offs:

(1) The parabiologists can pidgeonhole specimens they collect into one of at least 1,000 categories. In the 1996 Kikori Basin survey, they had to sort over 43,000 specimens into over 1,600 morphotaxa, represented by voucher specimens (Orsak & Easen 1996). The accuracy was impressive; resorting of a test sample yielded 97% correct identifications.

(2) Three full-time parabiologists, in only 14 months work in 1994, amassed a fully pinned, spread, and labeled collection, filling some 110 standard entomological drawers. In comparison, the Australian National Insect Collection's (Canberra, A.C.T.) PNG moth assemblage, acquired over a period of 30 years, fills some 500 drawers. This massive addition of specimens will prove useful in unraveling taxonomic obscurities and mysteries, a continual obstruction to research on tropical insects.

(3) The parabiologists are far more effective communicators of the value of biological diversity to tribal landowners, compared to expatriate scientists performing the same work. These moth community assessments have become a consistent part of rapid biological appraisal expeditions carried out in Papua New Guinea, and to-date, the moth-collecting parabiologists have been brought in for expeditions sponsored by the Papua New Guinea Department of Environment and Conservation, World Wildlife Fund-USA (Orsak and Easen, 1996), Research and Conservation Foundation of PNG, Pacific Heritage Foundation, and the PNG Institute of Medical Research (Orsak, 1996). The data has been used to assess biodiversity of specific sites for conservation management purposes. Additionally, we have used moth-collecting to demonstrate to customary landowners how biodiversity-rich their forests are. Light-trapping techniques can demonstrate that

vast numbers of species live in their forest, more than even their own in-depth, traditional knowledge, would lead them to expect. Such information-sharing is a purposeful attempt to impress upon customary landowers the exceptional value, known and unknown, of their forest habitats, as a prelude to conservation efforts.

The results of our surveys to-date suggest that moth diversity generally mirrors plant diversity (Orsak et al., 1995; Orsak and Easen, 1996), thus making moths a good tool for biodiversity assessments. *Alpha* values from PNG collections have ranged from 90 (1,800 metres elevation, southern New Ireland) to 333 (1,280 metres elevation; Kikori Basin, Gulf Province), fitting the general elevational trends found by Holloway (1987). Although results are not yet conclusive, comparisons of *alpha* values obtained from moth samples from slightly to moderately disturbed, compared to nearby undisturbed forests yielded higher *alpha* values for the latter (Orsak et al., 1995; Orsak, 1996). It is clear that not only moth species diversity, but also its morphological diversity changes from one site to another. We know that moth physical appearances (aspect diversity) vary with latitudinal diversity (Ricklefs and O'Rourke, 1975). It makes sense that species with 'outlier' morphologies, e.g. highly specialised antipredator colour patterns and postures are more likely to occur in exceptionally species-rich areas. Such 'appearance markers', easily discernible to the naked eye, could serve as indicators of exceptionally species-rich sites. This could be a far more efficient evaluation technique than sorting of thousands of specimens as we now do.

3. Studies of Insect Herbivores in Papua New Guinea: Host Specialization on Rainforest Trees

J. L. Gressitt initiated the Bishop Museum's ongoing faunistic surveys throughout New Guinea in 1955. In 1961, he established a field station in the NW part of Papua New Guinea, at Wau, which later became the Wau Ecology Institute (Miller, 1993). In 1987, Allen Allison and Scott Miller initiated a long-term research program at Bishop Museum, which aims at unraveling patterns of insect diversity in the rain forests of PNG. Most of the field work was performed at the Wau Ecology Institute and focused on insects collected from fagaceous trees by the pyrethrum knockdown technique (canopy fogging). The experimental design emphasized a single species of tree, *Castanopsis acuminitissima* (Fagaceae). We fogged this species, together with related (*Lithocarpus* and *Nothofagus*) and unrelated genera (of Burseraceae, Clusiaceae, Dipterocarpaceae, Elaeocarpaceae, Grossulariaceae, Juglandaceae, Lauraceae, Phyllocladaceae, Rosaceae, and Sapindaceae) at study sites located at 500 m, 1200-1400 m and 2100-2200 m. We fogged a total of 51 trees yielding more than 45,000 beetles (Coleoptera) alone.

Preliminary analyses of the beetles from selected trees have been published (Allison et al., 1993 - ten trees of Fagaceae at the three sites; and Allison et al., 1997- eight *Castanopsis acuminitissima* at mid elevation), but identification of the beetles is still not completed. The first analysis involved 4840 individual beetles representing 633 species in 54 families, and the second analysis was based on 3977 individuals representing 418 species in 53 families. We have decided to defer further analysis of the beetles until identifications have been completed so the entire data set is available. The logistic challenges in processing all the specimens generated by canopy fogging projects such as this one without benefit of in-country parabiologists has proven to be a major limitation (see Erwin, 1995 for further discussion). In addition to the beetle studies underway with G. Allan Samuelson and other collaborators, studies of the spiders are now underway with Jonathan Coddington and of the ants, bees and aculeate wasps with Roy Snelling.

In 1992, Yves Basset joined the research team at Bishop Museum and spent one year in

Wau to study the species richness and host specificity of leaf-chewing insects feeding on ten forest tree species belonging to unrelated plant families. One of the tree species under scrutiny was *Castanopsis acuminitissima*, to follow up on the previous project. Five out of ten species were canopy trees. Insects were collected using a wide variety of techniques, including interception traps, canopy fogging, clipping, hand collecting and beating. The emphasis was on leaf-chewing insects and this allowed simple tests of insect host specificity in the laboratory. Analyses contrasted the species richness, host specificity and similarity of leaf-chewing insects among host-trees. Two parabiologists were trained and helped with data collection, and also performed some crude sorting of the insect material. A total of 75,000 insects were collected, including at least 399 species of leaf-chewing insects (Basset et al., 1996ab; Basset, 1996).

Our current research project started at the Christensen Research Institute in Madang in 1994. It is focused on the local species richness and host specificity of leaf chewing insects feeding on 30 species of trees in lowland rainforest and coastal habitats. We are studying 15 species of *Ficus* (Moraceae) and 15 species from the family Euphorbiaceae, including 6 species of *Macaranga* (see http: // www.bishop.hawaii.org / bishop / natsci / ng / ngecol.html for details).

This study has to deal with challenges typical for other eco-entomological surveys of tropical habitats, in particular: (a) extremely species-rich insect faunas with many rare species, so that minimum sample size involves large numbers of specimens; (b) complex data reflecting patchy temporal and spatial distributions of insects, thus necessitating survey in a variety of habitats, sampling sites and numerous replicate samples; (c) presence of different life stages, of which usually only the adult is tractable for taxonomic studies; (d) large numbers of 'tourist' , not feeding species, obscuring patterns of host plant preferences; (e) lack of detailed ecological information on the host plant species; and (f) complex taxonomy of insects (e.g., sibling species) and lack of available taxonomic information and expertise.

Our approach to these problems involves the following steps: (a) collecting live insects from the vegetation using direct methods (i.e., hand collecting, beating), instead of techniques providing dead insect specimens and indirect evidence of the association with the host plant (e.g., light and malaise traps or canopy fogging); (b) massive sampling of a few tree species that are abundant locally to provide sufficient spatial and seasonal replicates; (c) rearing of juvenile specimens to provide adults tractable for taxonomic studies; (d) testing whether the insects collected on a particular host indeed are able to feed on this host under laboratory conditions; (e) collecting a variety of ecological data in parallel with insect sampling; (f) creating a customized computer identification database and immediate mounting of insects and their identification to morphospecies, rather than creating a back-log of unprocessed material. Morphospecies are later checked, and often identified, by specialists.

The manpower required to successfully perform this type of sampling programme on a sufficient scale is considerable. Our capacity was greatly enhanced in this respect by training local people as field and laboratory technicians ("parabiologists"). With a substantial investment of time and effort in parabiologist training, the objectives of even rather extensive research can be achieved with modest budgets and infrastructures, as our experience in PNG has shown. For example, our facilities in PNG consist of 40 m^2 of air conditioned lab space, one freezer, 2 insect cabinets, 2 stereo microscopes with fiber optics, 2 computers and a video camera suitable for digital photography. A resident scientist trains and works with 5 full-time parabiologists and with about 10 part-time village insect collectors.

The extent to which we succeeded in dealing with the above challenges can be illustrated by results from the first 26 months of our ongoing study: (a) about 29,200 leaf chewing insects were collected from the foliage of 30 tree species; (b) seven forest and coastal habitats, representing a complete successional series, were surveyed at four main sampling sites located within a 30 x 20 km area; more than 9,000 individual trees were visited 20,600 times; (c) approximately 5,800 caterpillars were reared to adults; (d) all 29,200 insects collected were subjected to feeding tests and 19,500 individuals testing positive were retained for further processing; (e) numerous characteristics of host trees (leaf specific weight, latex content, pubescence, expansion time and palatability, predation rate on the foliage, and tree density, size, and habitat preference) were measured for all 30 tree species; and (f) all 19,500 feeding individuals were and sorted to 546 morphospecies; 10,800 of them were mounted (most of the rest are caterpillars which we were unable to rear); in the next step, 42 colleagues provided taxonomic expertise on the insect and tree species and high quality material was made available for systematics research.

4. Host Specialization of Rainforest Insects: Consequences for Global Biodiversity Estimates

In his pioneering study of insect species diversity in rainforest canopy, Erwin (1982) suggested that there may be as many as 30 million species of arthropods, instead of the previously estimated 1.5 million species. This estimate results from a chain of extrapolations based on the Erwin's (1982) data on the local species richness of beetles associated with the tropical tree *Luehea seemannii* in Panama. Host specificity of rainforest herbivores proved to be one of the more controversial parameters entering these extrapolations. Characteristically, the attention focused more on theoretical aspects of the host specificity estimates (e.g. May 1990) than on the collecting of much needed empirical data (Basset 1992).

The study of ten rainforest tree species by Basset and collaborators (1996a; see above) provided extensive data to test Erwin's

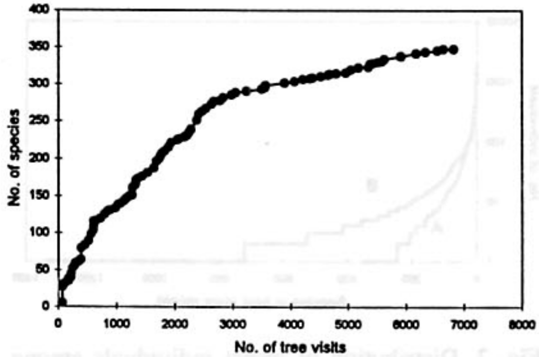

Fig. 1. Species accumulation curve for leaf-chewing herbivores feeding on 15 species of *Ficus*. Sampling effort measured as the number of tree visits.

assumptions on insect host specificity. Erwin guessed that about 20% of herbivores were monophagous, while our study yielded much lower proportion, about 4.3%. This new estimate would scale down the global estimate to 6.6 million arthropod species. Numerous complicating factors, discussed by Basset et al. (1996a), make even the corrected estimate unreliable. One of such problems is the effect of host plant phylogeny on the patterns of herbivore specialization. Replicated studies on both closely and distantly related plants from various taxa are needed for more general estimates of herbivore specificity.

Within the framework of our current study, we completed a survey of herbivore food preferences within a set of closely related plants, namely 15 species of *Ficus* (see Marquis, 1991 for similarly focused study on *Piper* spp.). Results of this study (Basset and Novotny, MS) can be used to illustrate problems plaguing the measurement of such a seemingly straightforward characteristic as the host specialization. Despite almost two years of sampling and 6,800 tree visits, we were unable to record all leaf-chewing species feeding on the 15 *Ficus* species (Fig. 1). Another serious problem was a high proportion of rare species in the samples, despite our sample size being as large as 13,193 insects. Among 349 species found

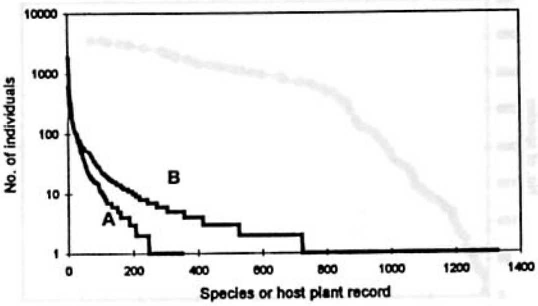

Fig. 2. Distribution of insect individuals among insect species (A) and among host plant records (B) for leaf-chewing herbivores feeding on 15 species of *Ficus*. Insect species (S=349) and insect-plant combinations (n=1328) are ranked by the number of individuals.

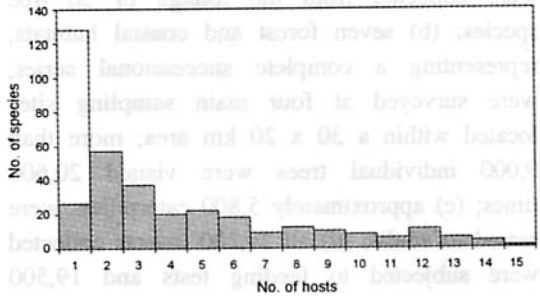

Fig. 3. Number of insect species collected and feeding on different number of *Ficus* species. The empty bar shows the number of singleton species. All species included (S=349).

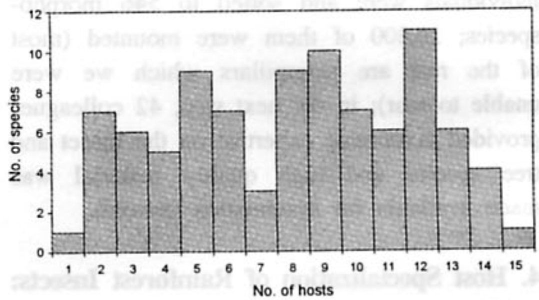

Fig. 4. Number of insect species collected and feeding on different number of *Ficus* species. Only species collected as N≥ 15 individuals are included (S=92).

confirmed to be feeding on the 15 *Ficus* species, 29% was represented by a single individual (Fig. 2). The existence of 1,328 insect - plant combinations (out of the 349 × 15 = 5,325 combinations possible) was documented, but almost half of them was supported by a single insect individual (Fig. 2).

Host plant range is more likely to be underestimated for rare than for abundant species, as well as for polyphagous than for specialized species. These sampling effects make any host specificity parameter used to characterize the whole community potentially biased. For instance, almost all of the large number of apparently monophagous species in our data are rare, most often singletons (Fig. 3). Records of singleton species do not convey any information concerning their host specificity, but it is easy to see how the number of host plants can be underestimated for other rare species as well. This bias can be especially large for polyphagous species; a herbivore feeding on all 15 *Ficus* hosts would have to be collected as at least 15 individuals, but many more in practice, in order to document its complete range of host plants. The pattern of host specificity looks indeed very different if only species found as N15 individuals are analyzed as most of them feed on several *Ficus* hosts (median 8 hosts; Fig. 4). The minimum sample size can be further increased to make host range estimates even more reliable, but this would exclude the majority of species from the analysis. The N15 specimens threshold already excluded 74% of species. Analysis restricted to only a small fragment of the community can produce biased estimates of host specificity if the latter is correlated with population size.

Only one monophagous species was retained in the data set after the application of N15 threshold for minimum sample size. This threshold was however set specifically for the analysis of polyphagous species so it might be unnecessarily high for description of the host plant range of specialists. In particular, monophagy can be tested against an alternative hypothesis that a given species feeds on two hosts, showing no preference for either of them. The binomial probability of finding all N individuals of such a herbivore on a single host is $P = 2 \times 0.5^N$. The N6 threshold is therefore needed in order to reject this hypothesis with $P<0.05$. There were 151 herbivore species collected as N6 specimens and five of them, or 3.3%, were recorded from only one *Ficus* host. Our estimate of 3.3% incidence of monophagy is probably still an overestimate as there is conservative 40 *Ficus* species in our study area, and numerous other potential hosts which were not studied.

5. Collaboration with Local Villagers: Insect Collectors and Parabiologists

The encyclopedic knowledge of the natural world by Papua New Guineans is well known and has been noted by several ecologists (e.g., Diamond, 1989) as well as being documented by Papua New Guineans themselves (e.g., Majnep and Bulmer, 1977). Papua New Guineans typically know hundreds of plant and animal species living in their forests and have developed detailed nomenclature systems for them in their local languages. Local plant names greatly facilitate communication and work with villagers. Traditional use of many rain forest plants means that villagers have detailed knowledge on their abundance, distribution and various aspects of their ecology. For instance, we were able to establish which species of birds and mammals feed regularly on figs of various species (Basset et al., 1997) as this was important information for hunting. Although the villagers' knowledge and nomenclature of insects is much less detailed than that of plants and vertebrates (e.g., Sillitoe, 1995), it is still easy for them to grasp differences between higher insect taxa and, for instance, learn differences between herbivore and predatory taxa.

Most of the human population of PNG live in villages in or near forested areas, practicing subsistence agriculture (Sekhran and Miller, 1996). In villages approached for collaboration there was almost always some, and often very substantial, interest in carrying out our research projects on their lands. We developed two main forms of participation by local villages in our research activities, namely in the jobs of (a) insect collectors and of (b) parabiologists. Most of our assistants are young people with formal education ranging from grade 6 to 10. Every potential collaborator starts as an insect collector. This entails brief training and subsequent independent field work, following a specified protocol. Our sampling methods usually include hand-collecting, beating and using small aspirators. Collaboration with village collectors can substantially increase the volume of field samples and enables simultaneous work at several locations. This advantage can be significant, especially with low-technology sampling protocols, which are limited more by available man-power then by expense of technical equipment. Hand-collecting of insects from tree foliage represents an extreme case in this respect, as village collectors can and do perform as well as professional ecologists in such sampling. With modest training, village youths can be invaluable field collectors, capable of following simple sampling protocols. This sampling is performed without supervision and collected insects are brought to our laboratory on the following day, alive, with information on host tree, number of trees sampled, and number of trees sampled (and tagged) for the first time.

6. Parabiologist Training: Merits and Rewards

The most capable and dedicated collectors are offered parabiologist training. This training represents a substantial investment of time and effort since parabiologists, in addition to field work, also execute simple field and laboratory experiments. Our training programmes follow in the footsteps of the National Institute of Biodiversity (INBio) in Costa Rica (e.g., Janzen, 1992) and of the Christensen Research Institute in PNG (Orsak, 1996), with an emphasis on computer techniques. Training and practical research are integrated, one with the other, as continuous "on the job" training. Parabiologist training, in the context of our research programmes, includes:

- General entomology and other science-related fields.
- Insect collecting with a wide range of techniques, including the use of single ropeclimbing to access tall trees.
- Insect rearing and laboratory feeding tests.
- Insect mounting and the curation of insect collections.
- Microscope work.
- Identification of insect herbivores to morphospecies, including dissection and examination of genitalia.
- Computing, particularly data input and management of insect databases.
- Use of digital photography and work with image processing software.

There are two areas in the training of parabiologist which we see as especially important, namely the identification of insect morphospecies and general computer literacy. Identification of morphospecies is difficult to learn but crucial for the quality of resulting data. Assigning an insect to a correct species among several hundreds typically dealt with in any rainforest insect study is a skill which must be based on solid knowledge of insect morphology. Morphospecies identification produced by non-specialists can be very consistent with similar data obtained by specialist taxonomists, but only if training standards of non-specialists are high (cf. Oliver and Beattie, 1996). We found this task greatly simplified by the use of the computer identification database, specifically developed for our project. This database serves also as a medium for storage and preliminary analysis of field data and as a teaching tool. It is based on the Microsoft Access 7.0 software and includes: digital images of insects; text fields for species diagnosis; taxonomic and ecological data; direct links to similar species; a glossary; and multiple ways of data sorting and filtering. Parabiologists have been trained not only in the use of the database for morphotyping insects, but also in database management and development. This entails entering new data, new species descriptions, new digital images and backing up updated files on ZIP cartridges. The parabiologists are also trained to shoot high quality pictures of insect specimens and retouch these pictures using image processing software. They use a SONY DXC 107 video camera hooked to a TV screen and to a frame grabber, which digitizes the picture and transfers it to the computer. The main advantages of using digital photography over more conventional scanning of slides is the speed and convenience at which the pictures can be included in the databases. We have developed a procedure of lightly sedating caterpillars with CO_2. This allows us to take good pictures of them and resume their rearing afterwards, thus allowing matching of reared adults with the earlier descriptions of caterpillars. Drawings of genitalia or other morphological characters can be scanned and incorporated into the database as well. Typically, databases hold several hundreds of species and, depending on the number of pictures associated with each species, represent 20-80 MB of memory space each. Insect databases can have especially large impact in three areas:

(1) Improved processing of insect material. Efficient sorting of established morphospecies can be achieved so that morphospecies which were never collected previously can be easily recognized and assigned accordingly. The parabiologists compare the digital pictures, the species' diagnosis, drawings of genitalia and insect specimens in reference collections, all at the same time. Data processing becomes nearly simultaneous to data collecting. Specimen backlogs for processing in virtually non-existent.

(2) Improved management of large and complex insect data sets. Our databases hold all the insect data recorded and are fully relational. Various preliminary analyses can be

performed directly.

(3) Improved training and teaching of parabiologists. Since the display of the digital pictures is immediate, the databases are constantly used as "flip-books". In this way, parabiologists quickly learn to recognize particular families or groups of similar species, and quickly grasp essentials of taxonomy. The value of our databases as a teaching tool is also enhanced by a glossary of entomological terms, explained by relevant texts and illustrations.

(4) Rapid dissemination of data among collaborators and users. In many countries, such databases can be directly linked to Internet for interactive use by international collaborators and access by world wide web by a much larger audience.

Although we had to create our own database because nothing was available at the time that met our requirements, other packages are now available that meet some of these needs. For example, the "Biota" program by Robert Colwell, developed for the "Arthropods of La Selva" project in Costa Rica, is now commercially available. Although a proliferation of tools is beneficial in providing options, we hope that standards for both data and metadata evolve rapidly to facilitate exchange of data between projects and archiving of the accumulated data (e.g., Michener et al., 1996).

As we move into increasingly specialized activities along the sequence of *field sampling - sample processing & insect mounting - insect morphotyping & computerised data management*, the relative efficiency of parabiologists compared to professional ecologists decreases (and the training need is increased). Some might argue that the work of parabiologists should be limited to only the simple tasks. We, however, see computer literacy as a crucial part of parabiologist training as they become independent of day-to-day supervision and guidance by scientists. Ability to perform various tasks independently on long-term basis (up to several months, if needed) is the main factor making large investment in parabiologist training rewarding in terms of research performance. Computer literacy is an essential part of this independence as it makes possible the tracking of results, checking the progress of experiments, and planning further work. It also facilitates potential extension of use of parabiologist skills to areas of ecological research other than insect collecting and processing. Moreover, from the standpoint of developing the human resources necessary to meet the biodiversity challenges of tropical countries, it is important to let parabiologists develop their skills as far as practical.

One such area relevant to our work is the measurement of plant and ecosystem variables in the course of the insect sampling. Insect studies in the tropics require large sampling effort in order to obtain interpretable data. This is often achieved at the expense of measuring potentially interesting variables which could be useful in the subsequent interpretation of insect data. Because of the large number (15) of tree species we study each year, the measurement of any variable is a demanding task. For instance, one of the factors of interest to us is predation pressure by ants, which is estimated from the proportion of 30 baits (termites) discovered by predators during 30 minutes exposure on the foliage of a particular tree (Olson 1992). With 20 replicates per tree species, measurement of this single variable requires 15 × 20 = 300 experiments per year, which means setting up 300 × 30 = 9,000 termite baits and a minimum of 20 full days of field work. Other variables we measure are similarly labor-intensive: tree abundance estimated along 150 forest transects, leaf expansion rates measured on 15 × 30 = 450 individual leaves, and feeding rates by a generalist herbivore on live and excised foliage (15 × 30 = 450 feeding tests on leaves *in situ* and 450 tests on excised leaves). Parabiologists are fully in charge of such experiments and observations.

7. Conclusions: Potential for Use of Parabiologists in Tropical Countries

Our projects based in Papua New Guinea

were greatly helped by the fact that the life style in rural areas makes people there pre-adapted for field work in a variety of ecological projects. This fact raises a question whether our approach can be repeated in other countries where conditions are different. Janzen's pioneering work with parataxonomists set a successful precedent in Costa Rica, which differs in many respects from PNG (e.g., Janzen et al., 1993). Recently, one of the authors (Y. B.) applied the parabiologist approach in yet another country, Guyana. Training and use of parabiologists was modeled on the PNG project and, despite many differences in sampling protocol as well as in local conditions, proved to be successful. The Guyana project is focused on herbivore communities feeding on seedlings of five rainforest canopy trees. The study area is located in a region which traditionally lacks local resident populations. Instead, the parabiologists are recruited from a "logging town" established about 20 years ago. They also include young people with little formal education, and their personal knowledge of rainforest habitats varies from case to case. Parabiologists are trained in independent field work, as well as in laboratory work using similar computer identification databases as in PNG. Similar to PNG, their participation in the project was crucial in execution of a massive sampling programme - monthly monitoring of insects on approximately 10,000 seedlings.

We believe that our sampling and processing protocols, which integrate low-cost collecting methods, training and computer technology can quickly tap reservoirs of young and motivated local people and engage them in the inventory of the wealth of biodiversity in many countries. This is a viable alternative to work with local university students as there is a negative correlation between local availability of such students and presence of rain forests. Our approach takes advantage of a combination of two elements present in local communities in many tropical countries, namely the existence of detailed local knowledge on natural history of forest plants and animals, and interest in developing this knowledge with the use of modern, high-technology (especially computer-related) approaches, rather than in traditional, customary ways. Parabiologist programmes can substantially improve our knowledge of rain forests as well as promote forest conservation. This is especially important in view of a slow progress in the inventory of rainforest biodiversity and a fast progress in its destruction (see e.g. Bernard and De Koninck, 1996 for deforestation rates in SE Asia). Involvement of village communities in ecological research clearly demonstrates to them the value of undisturbed forests on their lands (Orsak, 1993). It is important especially in PNG, where 97% of the land is under traditional tenure, controlled by local village communities. The only way to accomplish conservation of forests is for the local people to value their land for its biodiversity and long-term resources, rather than to use it for short-term monetary gain through exploitative resource extraction, such as logging (Sekhran and Miller, 1995). Parabiologists can be very important in explaining biodiversity issues to the local people as they are exposed to research environment, while still maintaining links with their village communities.

In conclusion, we anticipate that scientists of both developing and developed countries will rely increasingly on local assistants/parabiologists to carry out small-scale ecological projects in rainforest habitats. The parabiologist approach is relatively inexpensive, and highly efficient in terms of collecting data and biological material. Just as importantly, the strategy provides for transfer of knowledge on to the level of local communities, as well as increasing economic benefits to these communities.

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