

Report

A Generic, Computer-assisted Method for Rapid Vegetation Classification and Survey: Tropical and Temperate Case Studies

[Andrew Gillison](#)¹

ABSTRACT. Standard methods of vegetation classification and survey tend to be either too broad for management purposes or too reliant on local species to support inter-regional comparisons. A new approach to this problem uses species-independent plant functional types with a wide spectrum of environmental sensitivity. By means of a rule set, plant functional types can be constructed according to specific combinations from within a generic set of 35 adaptive, morphological plant functional attributes. Each combination assumes that a vascular plant individual can be described as a "coherent" functional unit. When used together with vegetation structure, plant functional types facilitate rapid vegetation assessment that complements species-based data and makes possible uniform comparisons of vegetation response to environmental change within and between countries. Recently developed user-friendly software (VegClass) facilitates data entry and the analysis of biophysical field records from a standardized, rapid, survey pro forma. Case studies are presented at a variety of spatial scales and for vegetation types ranging from species-poor arctic tundra to intensive, multitaxa, baseline biodiversity assessments in complex, humid tropical forests. These demonstrate how such data can be rapidly acquired, analyzed, and communicated to conservation managers. Sample databases are linked to downloadable software and a training manual.

INTRODUCTION

Conservation planners and managers face increasing demands for rapid resource appraisals that are relevant to management at local, regional, and global scales. Rapidly diminishing biodiversity resources and escalating concern about the impact of global change make it increasingly clear that there is a need for ready access to generic, low-input, high-return classification and survey methods. This level of urgency demands a break from traditional, logistically demanding methods that focus on highly detailed inventories of restricted areas with limited potential for extrapolation. Instead, the emphasis should be on methods that can provide a rapid overview of environmental variability and the manner in which biota respond to change along biophysical environmental gradients.

The purpose of this paper is to provide supporting information for two recently released, complementary, electronic Web-based packages. The first is a simple-language training manual in survey and classification methods designed for people with a limited ecological and taxonomic background, the second a user-friendly Windows-based program that facilitates data entry, the summary and analysis of metadata, and graphic output.

Both the classificatory and survey design approaches and the computer-based modules have been long in the making, necessarily requiring evaluation in a wide range of global environments. Two sample databases are attached, one representing a detailed biodiversity baseline study in a complex tropical landscape mosaic, the other containing plot data from a variety of global environments. Detailed analyses of the case studies used to illustrate the software application are set aside for a following paper and for this reason are not included here. As part of the rationale for the methods described here, it is necessary to provide a brief, comparative review of the limitations of some of the more common methods of survey design and vegetation classification and to introduce a relatively new approach that focuses on the adaptive responses of plants in a way that complements taxonomic and vegetation structural features. It is important at the outset to emphasize that the method described below is in no way intended to replace the use of taxa in inventories, but rather to complement their use, particularly in situations in which taxonomic information may be lacking, as is frequently the case in complex, tropical humid forests.

Most vegetation classification methods are essentially

¹Center for Biodiversity Management

visual-descriptive and based on combinations of dominant species and broad vegetation structure. These are generally intended to serve broad-scale geographic purposes and do not focus on the more dynamic aspects of adaptive responses to environment (cf. Dansereau 1957, Fosberg 1967, Kùchler 1967, Specht et al. 1974, Eiten 1978). Although the need for methods that do indicate vegetation adaptive response to environment was widely recognized among early ecologists, (Du Rietz 1931, Raunkiaer 1934, Schimper 1960), the further development of such methods was hampered by the lack of relevant ecophysiological theory and cost-efficient ways of analyzing complex data sets across varying environmental and geographic scales (Box 1981*a, b*, Woodward 1987, Belbin 1992). By far the most successful approach in terms of response-based plant features was that of Raunkiaer (1934), whose principal functional criterion was the position of the perennating bud during the most unfavorable season. However, the simple elegance of the Raunkiaerian system is, unfortunately, flawed in two significant aspects. The first is its inability to account for the many indeterminate "gray" areas that occur between different life forms, in particular phanerophytes and chamaephytes and the numerous cryptophytic (below-ground perennating organs) and lianoid modifications of these two life forms. Second, Raunkiaer's rather arbitrary provision of a logarithmic series of leaf size classes was the full extent of his descriptive format for a functional "leaf," a circumstance undoubtedly determined by the state of ecophysiological knowledge at the time. Subsequent modifications of Raunkiaer's system that were developed and applied in Western Europe and the Middle East (Braun-Blanquet 1932, Mueller-Dombois and Ellenberg 1974, Orshan 1983) failed to rectify this problem, producing instead a ponderous series of "open-ended" extensions of life forms. The largely arbitrary criteria of these systems provided little or no functional basis for defining the positioning and duration of photosynthetic tissue on an individual, despite the fact that both these features are critical to a plant's ability to adapt to its environment. These eurocentric approaches, derived from mainly species-poor, temperate environments, have little place in complex tropical vegetation with its extremes of richness in species and functional types. For this reason, they are rarely applied in practice. Later attempts to classify complex tropical rain forest using related physiognomic and structural features (Webb et al. 1976) were restricted to so-called "climax" forest and contained no generic capacity for accommodating other types of forest or disturbed or successional stages. Nevertheless, disturbed, highly dynamic

vegetation types are widespread in the tropics and are of increasing concern to conservation managers.

Other methods of characterizing vegetation based on life history strategies (Grime 1979, Noble and Slatyer 1980) focus on more specific models of plant behavior that demand a knowledge of life histories and unambiguous operational definitions of functional phenomena such as "stress" (cf. Grime 1979). Again, a pervasive lack of knowledge and understanding of these phenomena in complex vegetation limits their practical application. Despite these limitations, ecologists are moving steadily toward the development of "functional" approaches to classification. Although most are concerned with characterizing detailed ecosystem processes such as gene flow, disturbance, nutrient cycling, and photosynthesis (Franklin 1988, Körner et al. 1989, Martinez 1996), there is an increasing focus on the use of "functional types" that Diaz (1998) describes as "... sets of organisms showing similar responses to environmental conditions and having similar effects on the dominant ecosystem processes ..." (see also Cramer 1996, Cramer et al. 1999). This is an extension of an earlier definition by Shugart (1996), who used plant functional types (PFTs) to connote species or groups of species that have similar responses to a suite of environmental conditions. Functional types can be used to help reduce complex species groups to more manageable entities and to compare the responses of individuals, for example, between geographically remote locations in which environments and adaptive morphologies are similar but species differ. Whereas functional phenomena apply within a "gene-species-ecosystem" hierarchy, there is increasing debate about the role of species diversity in maintaining ecosystem function and whether or not species designations are the best method of distinguishing functional groupings (Johnson et al. 1996). In this sense, the perception of species "guilds" as functional assemblages (Schimper 1960, Johnson 1981) may need to be re-examined.

Many studies suggest that the measurement of biodiversity should include functional features or functional types as well as species (Fosberg 1967, Linder and Campbell 1979, Box 1981*a, b*, Gillison 1981, 1988, Nix and Gillison 1985, Cowling et al. 1994*a,b*, Huston 1994, Collins and Benning 1996, Martinez 1996, Woodward et al. 1996, Campbell et al. 1999). Although definitions of functional types vary (cf. Diaz 1998), most are commonly associated with guilds (Gillison 1981, Bahr 1982, Huston 1994, Gitay and Noble 1996, Shugart 1996, Smith 1996, Gillison

and Carpenter 1997, Gitay et al. 1999). Various workers have experimented with different sets of PFTs for widely different purposes and with varying success, e.g., for remote sensing (Nemani and Running 1996) or at the ecosystem level, particularly with respect to global change (Bugmann and Fischlin 1996, Nemani and Running 1996, Diaz and Cabido 1997). Species richness and abundance used alone and in the absence of other attributes of behavior and performance can seriously mislead and impede biodiversity assessment. In addition, parity in species richness between different sites does not guarantee equivalence in either genetic variability or response to environment. PFTs offer a means of avoiding this problem and are now widely considered a necessary and appropriate simplification of species diversity, and they have the advantage that ecosystem types often evolve more or less naturally from PFT assemblages (Cramer et al. 1999).

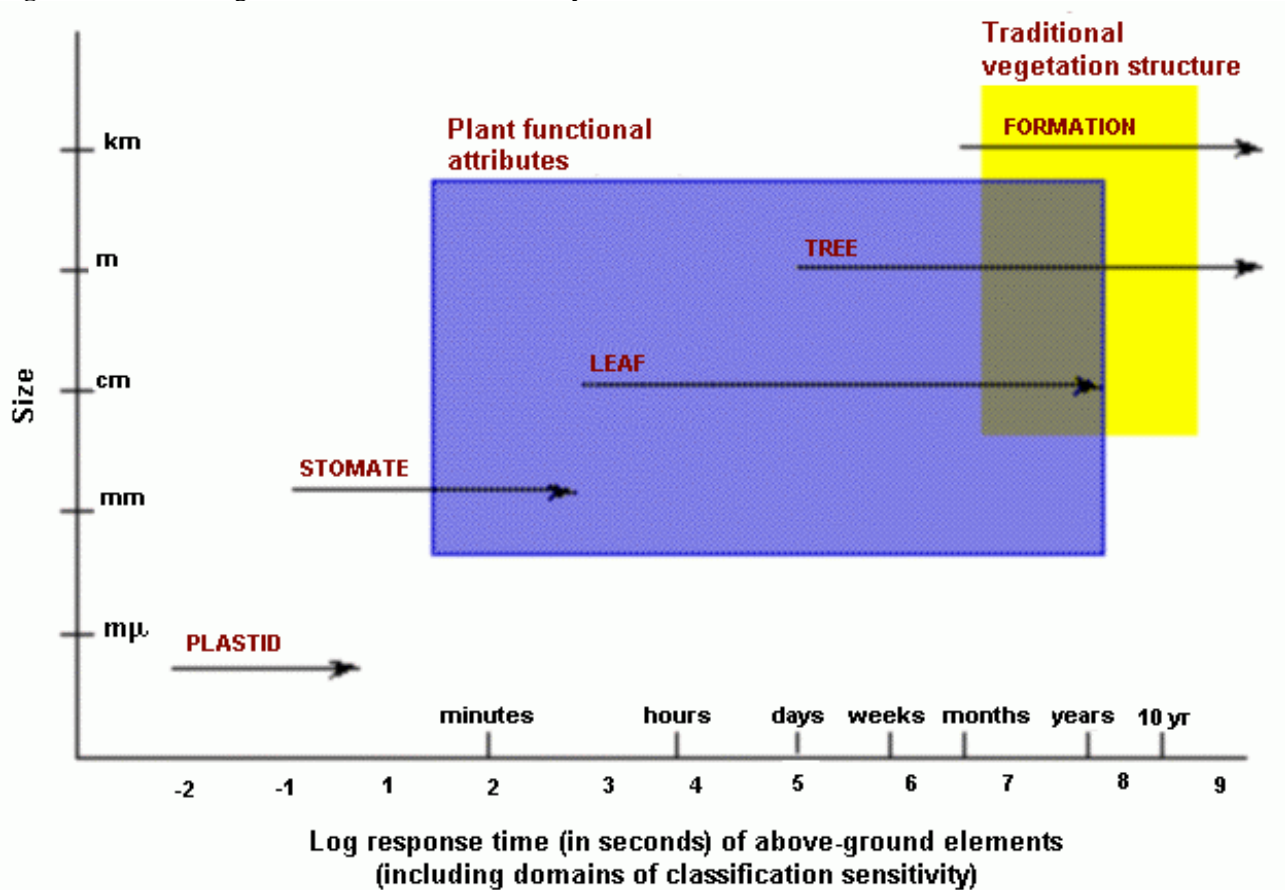
With regard to conservation management, variations in purpose and scale make it impossible to create a perfect vegetation classification system. However, there may be no need for the system to be perfect as long as its classificatory attributes are sufficiently robust for general purposes and can be modified to fit specific circumstances. At a global scale, for example, ecological comparisons between vegetation in similar environments in Africa and South America require a coupling mechanism that avoids the sole use of Linnean species. One possible mechanism is to use a generic set of functional types in combination with species and standardized vegetation structure. A key challenge is to devise a method that is logistically acceptable and has, at the same time, maximum sensitivity to plant responses at varying scales. Most current visual-descriptive methods are based on vegetation formation. Although these are useful from a geographic perspective, they are of limited relevance to conservation management that depends on far more sensitive classificatory criteria.

METHODS

With the above in mind, a formal systematic approach using plant functional types (Gillison 1981, 1988, 2000a, b, Gillison and Carpenter 1997) addresses the problem of selecting readily measureable plant

attributes that can be applied across a range of response scales (Fig.1). The method assumes that a plant individual can be described as a "coherent" functioning model by combining certain key units that are critical to ecophysiological performance and adaptation to environment. A minimum set of plant functional attributes (PFAs) is based on 35 functional elements bracketed across leaf size class, leaf inclination, leaf morphotype, modified Raunkiaerean life forms (see above), and above-ground rooting systems (Table 1). A semantic rule set is used to derive specific combinations of these elements to construct a plant functional type (PFT) or functional modus. Thus, a PFT for *Fagus grandifolia* in a deciduous conifer-broadleaf forest in the northeastern USA might be described as **no-la-do-de-ct-ph**, i.e., **no**tophyll leaf size class, **la**teral leaf inclination, **do**rsiventral leaf, **de**ciduous, with a green outer bark or cortex (**ct**), all attached to a **ph**anerophyte life form. This method is generic for all vascular plants. Using the rule set defined by Gillison and Carpenter (1997), a theoretical constellation of about 7.2×10^6 PFT combinations is possible. Although most of these do not occur in nature, the theoretically large number is of relatively trivial consequence for computing purposes. An examination of the statistical relationship between PFT richness and species richness on a global scale suggests that, in reality, the world's 300,000 or so plant species can probably be described by fewer than 4000 unique PFT combinations. An arbitrary table of transformation values is used to numerically weight a change from one PFA to another (Gillison and Carpenter 1997). These values are used to compute a "functional" distance matrix between individuals within a plot as well as between plots. This approach allows uniform quantitative comparisons to be made within and between plots and within and between countries. The relationship between species and PFTs is a many-to-many mapping (i.e., more than one species may occur in a PFT and vice versa). In this respect, phenotypic and genetic variability within a species may result in a species being expressed in more than one PFT or functional modus. Thus, the method can detect infra- as well as interspecific variability within and between sites. Such variability is potentially important for conservation managers when, for example, the within-species adaptive response to gradients of nutrient availability may have important implications for fauna management.

Fig. 1. Domains of vegetation classification sensitivity.



The PFT method based on functional modi (Gillison 1981) has been built into a software package called VegClass[®], whose version 1.6 is now available for beta testing. VegClass is Windows-based and uses a standard protocol to collate, store, and tabulate pro forma data. It can be used to generate graphic output of metadata and to export summary data to many spreadsheet and relational database programs (e.g., Microsoft Excel and Microsoft Access). It is designed to facilitate data entry from a standardized rapid survey pro forma that incorporates a minimum set of biophysical data recorded in a 40 x 5 m plot. Further details of the survey method are described in Gillison (2000a) and in the field training manual (VegMan) that accompanies the VegClass package. In brief, the site data include information on location; observers; date; latitude and longitude expressed as the degree, minute, and second measured by the Global Positioning System; elevation in meters; soil type (USDA soil taxonomy where possible) and depth in centimeters; litter depth in centimeters; and terrain

position. Vegetation structure includes mean canopy height in meters, percent crown cover (total, woody, and nonwoody), basal area in square meters per hectare, cover-abundance of bryophytes according to the Domin scale, cover-abundance of woody plants < 1.5 m tall, percent furcation index, and vegetation profile sketched to scale.

All vascular plant species and all unique PFTs are recorded in eight continuous 5 x 5 m quadrats in a 40 x 5 m plot. These quadrat data can be used by VegClass to construct, on demand, curves showing the ratios of species to area and PFT to area for any plot that may be used to indicate the level of sample representativeness of the vegetation being studied. The species:PFT ratio in a plot can give an idea of the degree to which functional "niche" space is occupied by different species. Typically, the ratio is higher in complex, species-rich, humid tropical forests than in highly disturbed, e.g., successional, vegetation that may have more variable light, water, and nutrient

Table 1. Plant functional attributes and elements used to generate plant functional types (functional modi) based on photosynthetic envelopes or functional "leaves" and their supporting vascular structures.

Attribute	Element	Description
Leaf size	nr	No repeating leaf units
	pi	Picophyll < 2 mm ²
	le	Leptophyll 2–25 mm ²
	na	Nanophyll 25–225 mm ²
	mi	Microphyll 225–2025 mm ²
	no	Notophyll 2025–4500 mm ²
	me	Mesophyll 4500–18,200 mm ²
	pl	Platyphyll 18,200–36,400 mm ²
	ma	Macrophyll 36,400–18 x 10 ⁴ mm ²
	mg	Megaphyll > 18 x 10 ⁴ mm ²
Leaf inclination	ve	Vertical > 30° above horizontal
	la	Lateral > 30° to horizontal
	pe	Pendulous > 30° below horizontal
	co	Composite
Leaf chlorotype	do	Dorsiventral
	is	Isobilateral or isocentric
	de	Deciduous
	ct	Cortic (photosynthetic stem)
	ac	Achlorophyllous (without chlorophyll)
Leaf morphotype	ro	Rosulate or rosette
	so	Solid three-dimensional
	su	Succulent
	pv	Parallel-veined
	fi	filicoid (fern), e.g., pteridophytes
	ca	Carnivorous, e.g., <i>Nepenthes</i>
Life form	ph	Phanerophyte
	ch	Chamaephyte
	hc	Hemicryptophyte
	cr	Cryptophyte
	th	Therophyte
	li	Liane
Root type	ad	Adventitious
	ae	Aerating, e.g., pneumatophore
	ep	Epiphytic
	hy	Hydrophytic
	pa	Parasitic

regimes with more available, albeit temporary, niches than climax forest. This ratio is automatically computed by VegClass. All species and PFT records consist of presence-absence data recorded in binary format. The fact that there is no longer any need for detailed counts of individuals greatly improves survey efficiency, although another result is that standard species diversity indices (e.g., Shannon-Wiener, Simpson, etc.) cannot be computed. To compensate for this, VegClass can be used to compute "functional diversity" in a way that is analogous to species diversity but that uses instead the number of species per PFT. The essential difference is that this is not a spatially dependent measure but more a theoretical measure of "evenness" and "dominance" expressed in relative terms (Gillison 2000a, b). In this way, functional diversity can be computed for the indices of Shannon-Wiener (H') and Simpson and for Fisher's alpha. Finally, another potentially useful PFT-based measure is defined as "plant functional complexity" (PFC), which is the total minimum-spanning-tree distance of a set of PFTs within a plot derived from the functional distance matrix. Both PFC and functional diversity indices have been found useful in biodiversity assessments in complex tropical land-use mosaics (Gillison 2000b, Gillison and Liswanti 1999). Graphic output from VegClass can be used to assist interpretation of within- and between-plot relationships for all the quantitative variables recorded via the pro forma.

CASE STUDIES

Examples of the ways in which data are compiled and analyzed are contained in the VegMan file, which also includes a sample plot. Appendix 1 of this paper presents a database containing 100 sites selected from a much larger database that covers a wide range of global environments. The full database can only be read using VegClass software, although certain sections of it can be opened in Microsoft Access. Because the database contains data entered in earlier versions of the software, authorities for botanical names may not always be stored in the column allocated for that purpose in version 1.6. Similarly, data records for contiguous 5 x 5 m quadrats are not available prior to June 1998, because only whole-plot totals were recorded up to that time. Recent pro forma changes now also disaggregate total crown cover percent into percent crown cover of woody plants and percent crown cover of nonwoody plants. The reason for this change is to enhance ecological discrimination between plots in which total crown cover may be

identical even though one plot is totally woody and the other herbaceous. This database is made available to allow exploration of patterns of vegetation structure and of plant functional types (PFTs) and plant functional attributes (PFAs) in particular. This should permit the user to gain a sense of how such patterns vary along latitudinal and elevational gradients and among disturbance regimes.

Appendix 2 presents seven figures illustrating the sets of curves that express the ratios of species to area, PFT to area, and species/PFT to area for a variety of vegetation types. Many of these sites are included in Appendix 1, and the graphs can be generated on demand through the VegClass graphing option. Relatively high, upward-turning ratios are evident in species-rich intact rain forest, where many species collapse into fewer PFTs. Patterns in secondary forest are chaotic, possibly because of the indeterminacy of that classification category. Species-rich Brazilian cerrado (woodland savannas) show very different patterns from those of savannas elsewhere, which are poorer in species but where rapid equilibrium is reached after the first quadrat. Agroforests parallel rain forests in richness but otherwise exhibit similar responses between countries (jungle rubber in Sumatra and jungle cocoa in Cameroon). Species:PFT ratios plateau rapidly in industrial plantations of mature oil palm in Brazil and Papua New Guinea, achieving almost identical values. In both Cameroon and Sumatra, species-poor cassava gardens and newly opened subsistence gardens achieve equilibrium after the first few quadrats, a pattern that is analogous to short-term fallows dominated by Asteraceae such as the frequently invasive *Chromolaena odorata*.

DISCUSSION

The detailed sample database contained in the VegClass package demonstrates how comprehensive data can be recorded in a well-supported logistic environment. Appendix 1 illustrates typical situations in which many species data are lacking due to the opportunistic way in which they were collected. It also reflects real-world problems facing surveyors in highly complex tropical forests where botanical assistance is frequently limited and where many species may be unknown or else new to science. Whereas absolute trends are elusive, in the curves for the species:area, PFT:area, and species/PFT:area ratios displayed in Appendix 2 there are nevertheless some congruent patterns among certain vegetation types that are also reflected between countries. Although further work is

clearly needed to elucidate such patterns in a more ecologically meaningful way, the procedure may serve as a tool for developing new theories to explain how ecological niches are filled in highly dynamic environments. The results of ecoregional baseline surveys conducted in a number of different countries (Cameroon, Indonesia, Thailand, Brazil, and Perú) using the method described here have shown improvements in ecological interpretation when plant functional types (PFTs) are included (Gillison 2000a, b). The use of PFTs in intensive, multitaxa, baseline biodiversity surveys in Sumatra (Bignell 2000, Jepson and Djawardi 2000, Jones et al. 2000) has also improved the capacity of such surveys to develop useful surrogates for biodiversity assessment. More detailed discussion of the ecological significance of these outputs will be published elsewhere.

The training manual was developed and refined through a series of training workshops in Brazil, Cameroon, Indonesia, Perú, the Philippines, Thailand, and Vietnam. Although much could be added to this manual, it is designed for use by people whose first language is not English and who may have only limited ecological and botanical experience. At the time of writing, a Portuguese (Brazilian) version of the CD-ROM had just been completed. Other multilingual versions are anticipated. All the data included in the database examples provided were collected from a standard 40 x 5 m plot as described in the *Methods* section. Although ecologists will no doubt continue to debate the question of plot size, the one used here evolved over many years of surveying by the author in a wide range of global environments. Although the area (200 m²) is arguably small, it has the advantage of being easy to lay out and does not fatigue observers to the degree induced by larger plots. Its smaller size also makes it suitable for targeting relatively cryptic habitats such as stream banks, forest edges, small home gardens, forest clearings, etc. Many such plots can be readily established across a wide-ranging environmental traverse. The use of the sample-area asymptotes provides an immediate indication of sample representativeness and alpha and beta diversity, for example, in a humid tropical lowland forest. High beta diversity as indicated by continuously rising curves suggests that additional plots are needed to achieve satisfactory sample asymptotes.

IMPLICATIONS FOR CONSERVATION MANAGEMENT

For managers who require ready access to baseline information about the underlying natural resource and the impact of land use and other disturbances on this resource, the method described above can provide a cost-effective solution. This is especially true when the VegClass approach is used in conjunction with a gradient-based survey design, for example, along land-use intensity gradients in combination with hierarchically nested environmental gradients (e.g., rainfall seasonality, thermal gradients, soil and parent rock type, etc.). A gradient-based design of this type is encapsulated in the gradsect method of Gillison and Brewer (1985) and has been successfully evaluated in a wide range of environments for both plants and animals (Austin and Heyligers 1991, Wessels et al. 1998). In forestry management, this method has been found to provide more efficient prediction of site productivity potential in mixed-species forests (Vanclay et al 1997). The georeferenced site data facilitate Geographic Information Systems mapping of land units and habitat types and serve as a sensitive basis for monitoring change. Shifts in plant functional types (PFTs) are readily apparent in disturbed areas and respond quickly to openings in the forest canopy. The quantitative nature of the attributes also facilitates statistical analysis. When compared with more traditional approaches to inventory, the VegClass method is more cost-efficient in terms of logistics and the acquisition of, for example, biodiversity baseline data, especially when information is required about the distribution and performance of biota along environmental gradients. Using the VegClass approach, a typical plot in a complex, humid tropical lowland forest takes about 3 h to complete with experienced observers. The method is particularly well suited to rapid technology transfer as evidenced by successful training workshops in a number of developing countries. The generic nature of the system also facilitates data networking within and between countries.

In Sumatra, Indonesia, this method proved useful in locating and identifying what may be one of the world's richest sites for vascular plant species and PFTs (see http://www.worldwildlife.org/species/attachments/tess_o_nilo.pdf). In a logged-over forest in Riau Province, extraordinarily high numbers of mostly woody species and PFTs (66 and 35, respectively) were recorded in the first 5 x 5 m quadrat, with a total of 217 species

Fig. A.1. Curves for intact rain forest.

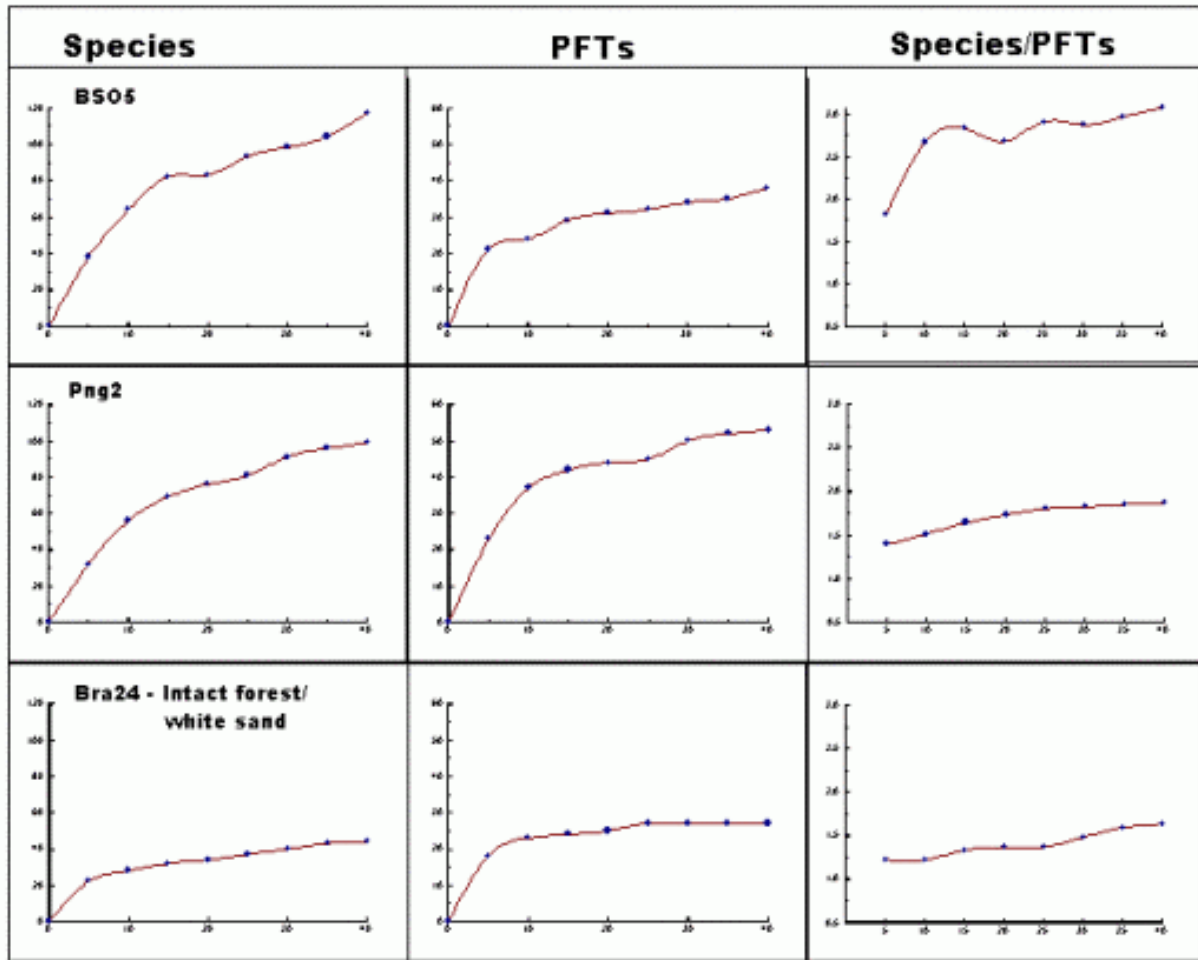


Fig. A.2. Curves for secondary forest.

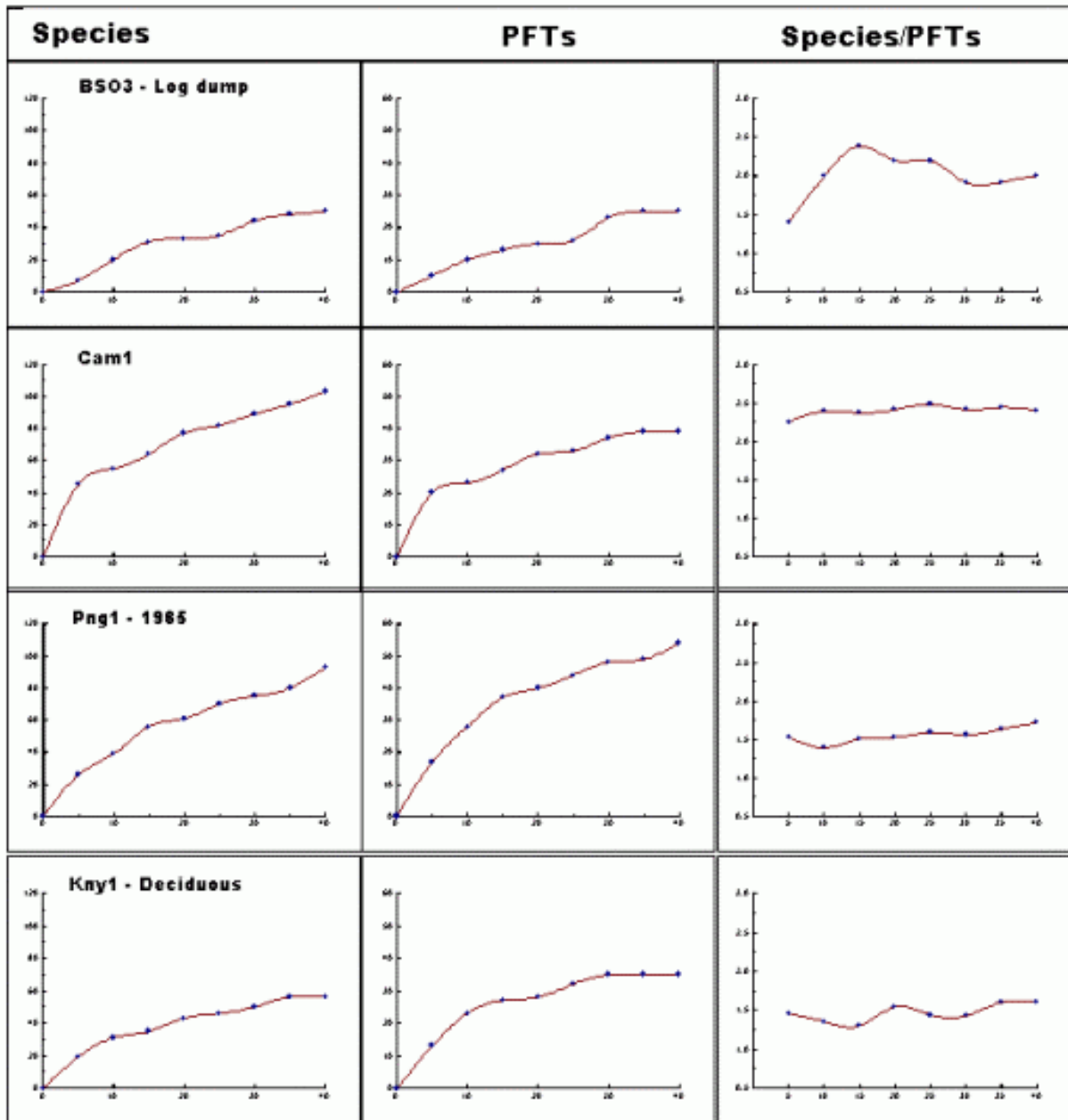


Fig. A.3. Curves for savannas.

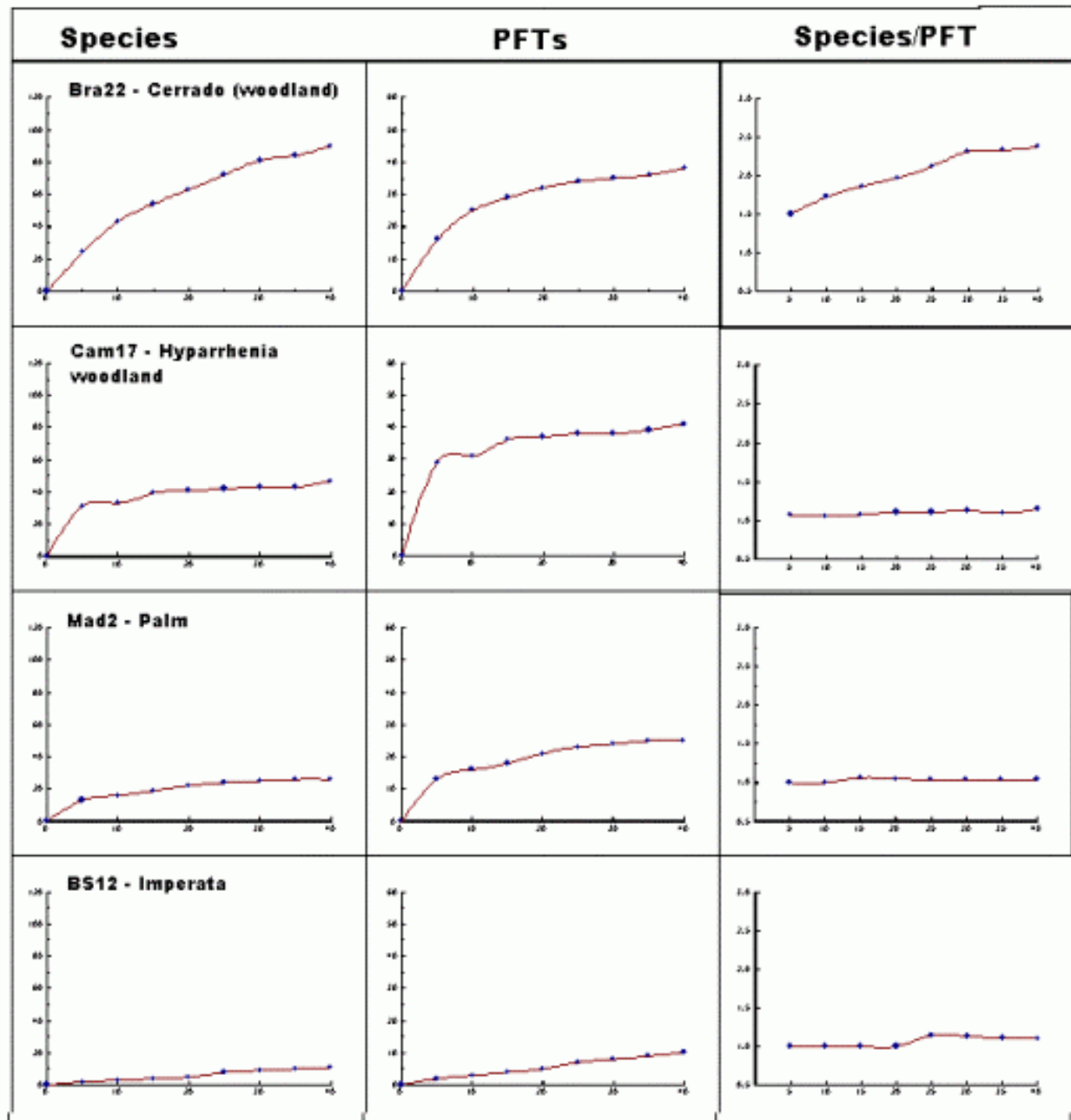


Fig. A.4. Curves for agroforests.

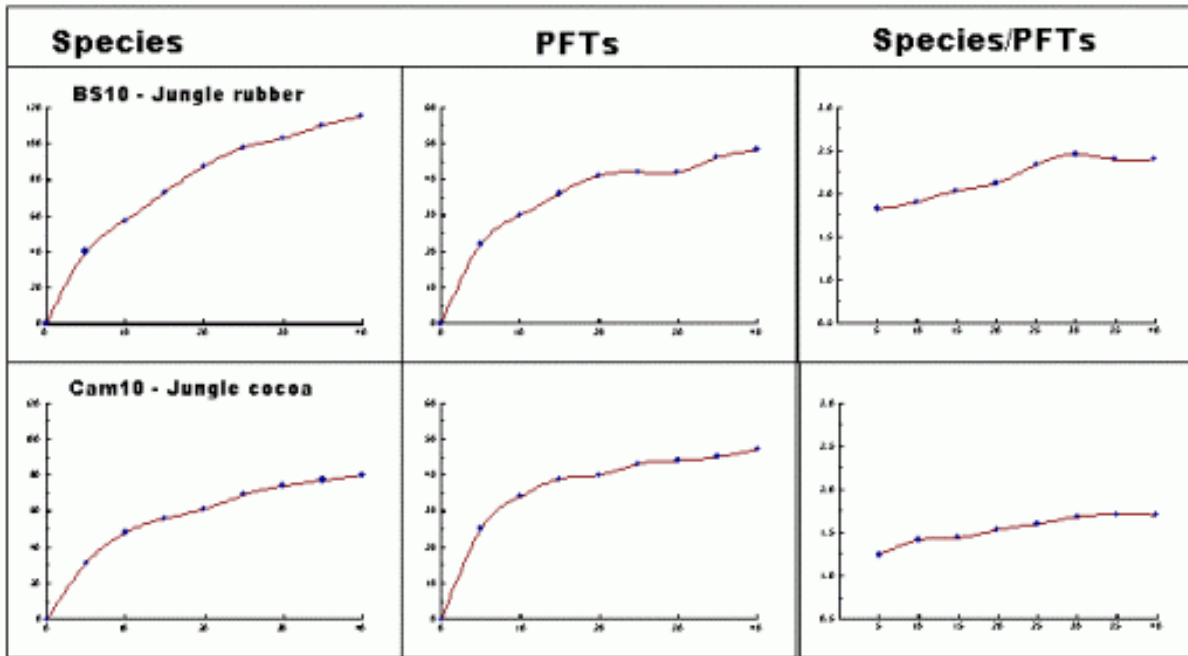


Fig. A.5. Curves for plantations.

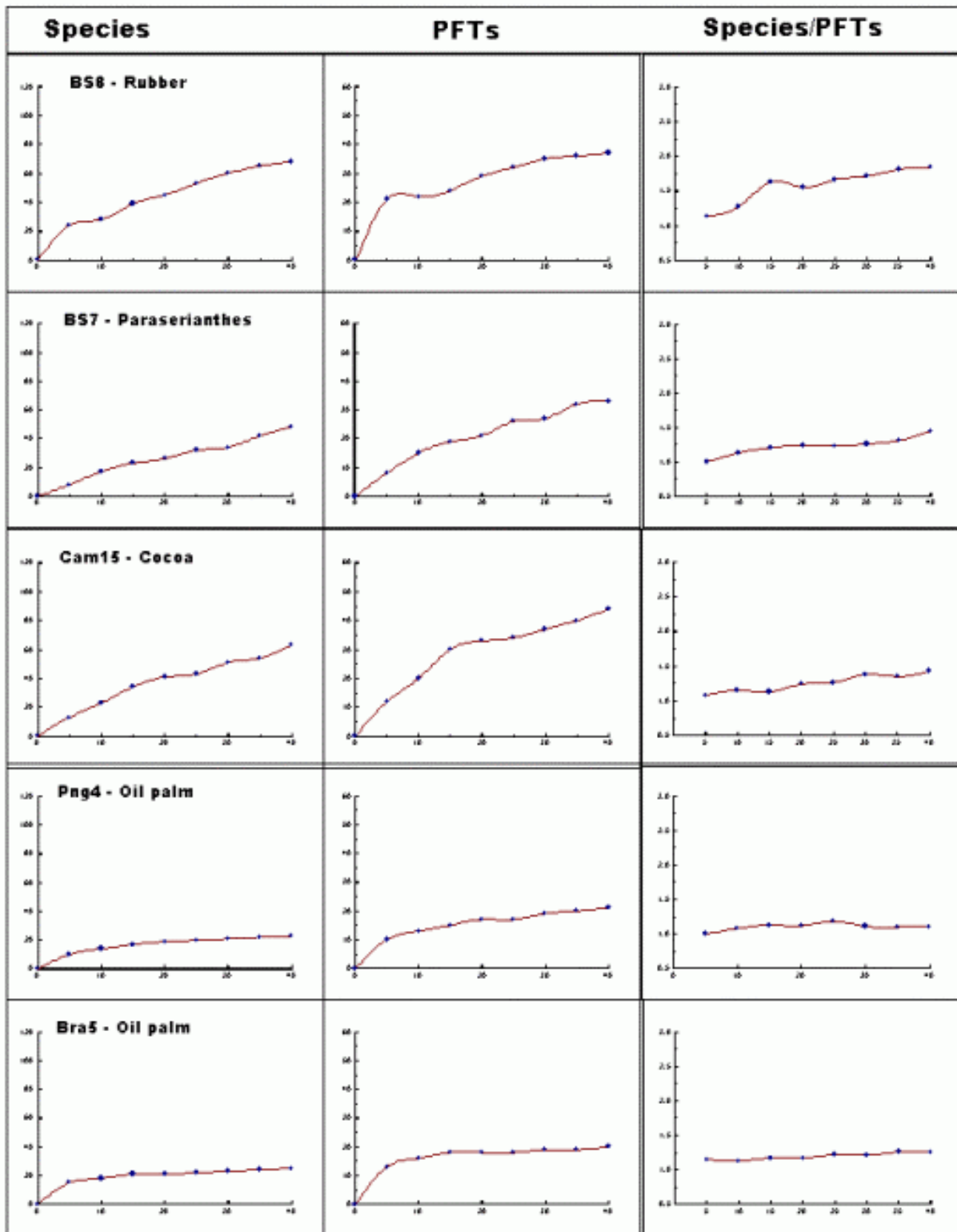


Fig. A.6. Curves for cassava.

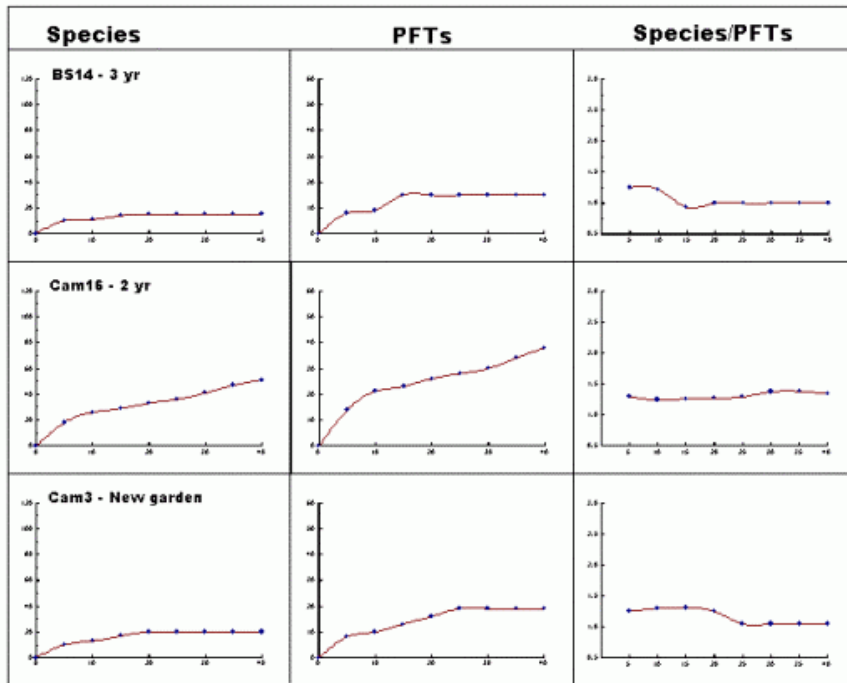
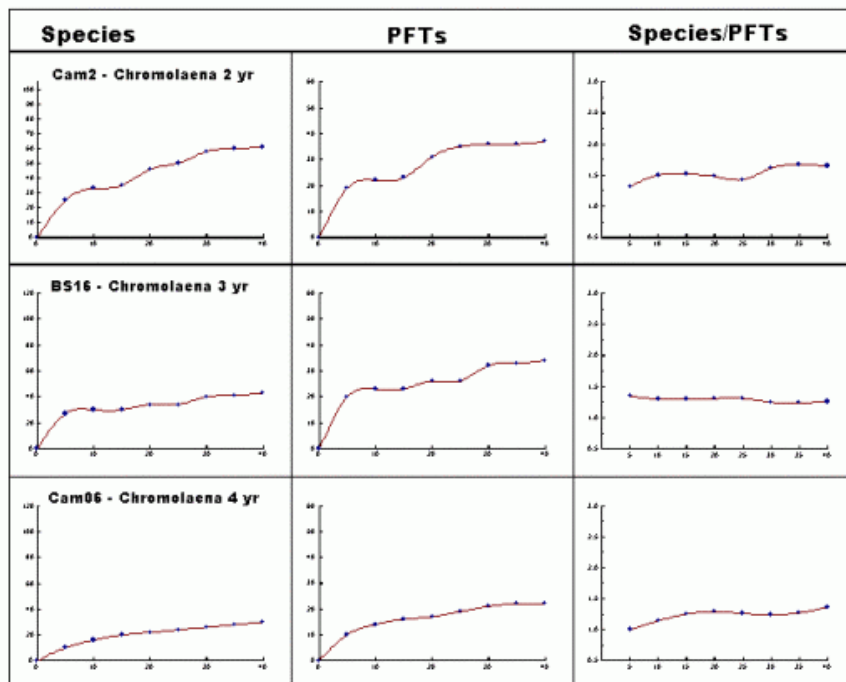


Fig. A.7. Curves for fallow areas.



LITERATURE CITED

- Austin, M. P., and P. C. Heyligers.** 1991. New approaches to vegetation survey design: gradsect sampling. Pages 31-37 in C. R. Margules and M. P. Austin, editors. *Nature conservation: cost effective survey and data analysis*. CSIRO, Melbourne, Australia.
- Bahr, L. M.** 1982. Functional taxonomy: an immodest proposal. *Ecological Modelling* 15:211-233.
- Belbin, L.** 1992. *PATN Pattern Analysis Package; technical reference*. CSIRO, Division of Wildlife and Ecology, Canberra, Australia.
- Bignell, D. E., E. Widodo, F. X. Susilo, and H. Suryo.** 2000. Soil macrofauna: ground-dwelling ants, termites, other macroarthropods and earthworms. Pages 91-127 in A. N. Gillison. *Above-ground Biodiversity Assessment Working Group summary report 1996-99: impact of different land uses on biodiversity*. International Centre for Research in Agroforestry (ICRAF), Nairobi, Kenya.
- Box, E. O.** 1981a. Predicting physiognomic vegetation types with climate variables. *Vegetatio* 45:127-139.
- Box, E. O.** 1981b. *Macroclimate and plant forms: an introduction to predictive modelling*. Junk, The Hague, The Netherlands.
- Braun-Blanquet, J.** 1932. *Plant sociology: the study of plant communities*. McGraw-Hill, New York, New York, USA.
- Bugmann, H., and A. Fischlin.** 1996. Simulating forest dynamics in a complex topography using gridded climatic data. *Climatic Change* 34:201-211.
- Campbell, B. D., D. M. Stafford-Smith, and A. J. Ash.** 1999. A rule-based model for functional analysis of vegetation change in Australian grasslands. *Journal of Vegetation Science* 10:723-730.
- Collins, S. L., and T. L. Benning.** 1996. Spatial and temporal patterns in functional diversity. Pages 253-280 in K. J. Gaston, editor. *Biodiversity: a biology of numbers and difference*. Blackwell Science, Oxford, UK.
- Cowling, R. M., K. J. Esler, G. F. Midgley, and M. A. Honig.** 1994a. Plant functional diversity, species diversity and climate in arid and semi-arid southern Africa. *Journal of Arid Environments* 27:141-158.
- Cowling, R. M., P. J. Mustart, H. Laurie, and M. B. Richards.** 1994b. Species diversity; functional diversity and functional redundancy in fynbos communities. *South African Journal of Science* 90:333-337.
- Cramer, W.** 1996. Using plant functional types in a global vegetation model. Pages 271-288 in T. M. Smith, H. H. Shugart, and F. I. Woodward, editors. *Plant functional types: their relevance to ecosystem properties and global change*. Cambridge University Press, Cambridge, UK.
- Cramer, W., H. H. Shugart, I. R. Noble, F. I. Woodward, H. Bugmann, A. Bondeau, J. A. Foley, R. H. Gardner, W. K. Lauenroth, L. F. Pitelka, and R. W. Sutherst.** 1999. Ecosystem composition and structure. Pages 190-228 in B. H. Walker, W. L. Steffen, J. Canadell, and J. S. I. Ingram, editors. *The terrestrial biosphere and global change*. International Geosphere-Biosphere Programme Book Series, Number 4. Cambridge University Press, Cambridge, UK.
- Dansereau, P.** 1957. *Biogeography: an ecological perspective*. Ronald Press, New York, New York, USA.
- Diaz, S.** 1998. The effects of global change on functional group diversity. Page 18 in E. Huber-Sannwald and V. Wolters, editors. *Effects of global change on biodiversity and ecological complexity; report of EU/TERI-IGBP/GCTE-DIVERSITAS Workshop Oct. 20-22, 1997*. Global Change and Terrestrial Ecosystem (GCTE) International Project Office, Canberra, Australia.
- Diaz, S., and M. Cabido.** 1997. Plant functional types and ecosystem function in relation to global change. *Journal of Vegetation Science* 8:463-474.
- Du Rietz, G. E.** 1931. Life forms of terrestrial flowering plants. *Acta Phytogeographica Suecica* 3:1-95.
- Eiten, G.** 1978. Delimitation of the cerrado concept. *Vegetatio* 36: 169-178.
- Fosberg, F. R.** 1967. A classification of vegetation for general purposes. Pages 73-120 in G. F. Peterken, editor. *Guide to the checklist for I.B.P. areas*. I.B.P. Handbook, Number 4. Blackwell Scientific, Oxford, UK.
- Franklin, J. F.** 1988. Structural and functional diversity in temperate forests. Pages 166-175 in E. O. Wilson and F. M. Peter, editors. *Biodiversity*. National Academy Press, Washington, D.C., USA.
- Gillison, A. N.** 1981. Towards a functional vegetation classification. Pages 30-41 in A. N. Gillison and D. J. Anderson, editors. *Vegetation classification in Australia*. CSIRO and Australian National University Press, Canberra, Australia.
- Gillison, A. N.** 1988. *A plant functional proforma for dynamic vegetation studies and natural resource surveys*. Technical Memorandum, Number 88/3. CSIRO, Division of Water Resources, Canberra, Australia.
- Gillison, A. N.** 2000a. Rapid vegetation survey. Pages 25-38 in A. N. Gillison. *Above-ground Biodiversity Assessment Working Group summary report 1996-99: impact of different land uses on biodiversity*. International Centre for Research in Agroforestry (ICRAF), Nairobi, Kenya.
- Gillison, A. N.** 2000b. Summary and overview. Pages 19-24

in A. N. Gillison. *Above-ground Biodiversity Assessment Working Group Summary Report 1996-99: impact of different land uses on biodiversity*. International Centre for Research in Agroforestry (ICRAF), Nairobi, Kenya.

Gillison, A. N., and K. R. W. Brewer. 1985. The use of gradient directed transects or gradsects in natural resource surveys. *Journal of Environmental Management* **20**:103-127.

Gillison, A. N., and G. Carpenter. 1997. A generic plant functional attribute set and grammar for dynamic vegetation description and analysis. *Functional Ecology* **11**:775-783.

Gillison, A. N., and N. Liswanti. 1999. Biodiversity and productivity assessment for sustainable agroforest ecosystems, Mae Chaem, Northern Thailand: preliminary report. Part D in A. N. Gillison. *Above-ground Biodiversity Assessment Working Group summary report 1996-99: impact of different land uses on biodiversity*. International Centre for Research in Agroforestry (ICRAF), Nairobi, Kenya.

Gitay, H., and I. R. Noble. 1996. What are functional groups and how should we seek them? Pages 3-19 in T. M. Smith, H. H. Shugart, and F. I. Woodward, editors. *Plant functional types: their relevance to ecosystem properties and global change*. Cambridge University Press, Cambridge, UK.

Gitay, H., I. R. Noble, and J. H. Connell. 1999. Deriving functional types for rain-forest trees. *Journal of Vegetation Science* **10**:641-650.

Grime, J. P. 1979. *Plant strategies and vegetation processes*. Wiley, Chichester, UK.

Huston, M. A. 1994. *Biological diversity: the coexistence of species in changing landscapes*. Cambridge University Press, Cambridge, UK.

Jepson, P., and Djarwadi. 2000. Birds. Pages 41-53 in A. N. Gillison. *Above-ground Biodiversity Assessment Working Group summary report 1996-99: impact of different land uses on biodiversity*. International Centre for Research in Agroforestry (ICRAF), Nairobi, Kenya.

Johnson, R. A. 1981. Application of the guild concept to environmental impact analysis of terrestrial vegetation. *Journal of Environmental Management* **13**:205-222.

Johnson, K. H., K. A. Vogt, H. J. Clark, O. J. Schmitz, and D. Vogt. 1966. Biodiversity and the productivity and stability of ecosystems. *Trends in Ecology and Evolution* **11**:372-377.

Jones, D. T., F. X. Susilo, D. E. Bignell, and H. Suryo. 2000. Terrestrial insects: species richness, functional diversity and relative abundance of termites under different land use regimes. Pages 128-139 in A. N. Gillison. *Above-ground Biodiversity Assessment Working Group summary*

report 1996-99: impact of different land uses on biodiversity. International Centre for Research in Agroforestry (ICRAF), Nairobi, Kenya.

Körner, C., M. Neumayer, S. Pelaez Menendez-Riedl, and A. Smeets-Scheel. 1989. Functional morphology of mountain plants. *Flora* **182**:353-383.

Küchler, A. W. 1967. *Vegetation mapping*. Ronald Press, New York, New York, USA.

Linder, P., and B. M. Campbell. 1979. Towards a structural-functional classification of fynbos: a comparison of methods. *Bothalia* **12**:723-729.

Martinez, N. D. 1996. Defining and measuring functional aspects of biodiversity. Pages 114-148 in K. J. Gaston, editor. *Biodiversity: a biology of numbers and difference*. Blackwell Scientific, Oxford, UK.

Mueller-Dombois, D., and H. Ellenberg. 1974. *Aims and methods of vegetation ecology*. Wiley, New York, New York, USA.

Nemani, R., and S. W. Running. 1996. Implementation of a hierarchical global classification in ecosystem function models. *Journal of Vegetation Science* **7**:337-346.

Nix, H. A., and A. N. Gillison. 1985. Towards an operational framework for habitat and wildlife management. Pages 39-45 in J. Kikkawa, editor. *Wildlife management in the forests and forestry-controlled lands in the tropics and the southern hemisphere*. IUFRO S1.08. International Union of Forest Research Organizations, Vienna, Austria. Available online at <http://www.asb.cgiar.org/PDFwebdocs/Aboveground%20Part%20C-Sec1-3.pdf>.

Noble, I. R., and R. O. Slatyer. 1980. The use of vital attributes to predict successional changes in plant communities subject to recurrent disturbances. *Vegetatio* **43**:5-21.

Orshan, G. 1983. Approaches to the definition of Mediterranean growth forms. *Ecological Studies* **43**:86-100.

Raunkiaer, C. 1934. *The life forms of plants and statistical plant geography*. Clarendon Press, Oxford, UK.

Schimper, A. F. W. 1960. *Plant geography upon a physiological basis*. Reprint of 1903 edition. Lubrecht and Cramer, Port Jervis, New York, New York, USA.

Shugart, H. H. 1996. Plant and ecosystem functional types. Pages 20-43 in T. M. Smith, H. H. Shugart, and F. I. Woodward, editors. *Plant functional types: their relevance to ecosystem properties and global change*. Cambridge University Press, Cambridge, UK.

Smith, T. M. 1996. Examining the consequences of classifying species into functional types: a simulation model analysis. Pages 319-340 in T. M. Smith, H. H. Shugart, and

F. I. Woodward, editors. *Plant functional types: their relevance to ecosystem properties and global change*. Cambridge University Press, Cambridge, UK.

Specht, R. L., M. E. Roe, and V. H. Broughton. 1974. Conservation of major plant communities in Australia and Papua New Guinea. *Australian Journal of Botany (Supplementary Series)* 7:1-667.

Vanclay, J. K., A. N. Gillison, and R. J. Keenan. 1997. Using plant functional attributes to quantify site productivity and growth patterns in mixed forests. *Forest Ecology and Management* 94:149-163.

Webb, L. J., J. G. Tracey, and W. T. Williams. 1976. The value of structural features in tropical forest typology. *Australian Journal of Ecology* 1:3-28.

Wessels, K. J., A. S. van Jaarsveld, J. D. Grimbeek, and M. J. van der Linde. 1998. An evaluation of the gradsect biological survey method. *Biodiversity and Conservation* 7:1093-1121.

Woodward, F. I. 1987. *Climate and plant distribution*. Cambridge University Press, Cambridge, UK.

Woodward, F. I., T. M. Smith, and H. H. Shugart. 1996. Defining plant functional types: the end view. Pages 355-359 in T. M. Smith, H. H. Shugart, and F. I. Woodward, editors. *Plant functional types: their relevance to ecosystem properties and global change*. Cambridge University Press, Cambridge, UK.