ANALYSIS OF THE PHYTOGEOGRAPHICAL SAMPLE FOR VEGETATION MAPPING IN THE BRAZILIAN AMAZON

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ABSTRACT

What are the best botanical criteria for selecting priority conservation areas in Amazonia? Are botanical endemism centers (also known as Pleistocene forest refugia) real or atifacts of sampling? How can remote sensing tools be combined with traditional botanical field work in improving the data base, permitting us to compare and rank the importance of different vegetation types or phytogeographic regions? Here we provide at least partial answers to these questions.

1. INTRODUCTION

Well over 100 man-years have been spent in the field in the Brazilian Amazon collecting botanical specimens for herbaria. Approximately 300,000 different vascular plant collections have been made of perhaps 25,000 different species native to the region. Most collections are accompanied by labels which provide location data, so that geographic ranges of species can be determined. By superimposing range data for hundreds of species, some workers have attempted to pinpoint centers of endemism for woody angiosperms (Prance, 1973, 1982a, 1982b, 1987). Conservation planners have applied this work in recommending priority sites for national parks in Brazil (Wetterberg & Jorge Padua, 1978). Mapping of plant distributions as revealed by herbarium data from taxonomic monographs continues to be an important means of locating centers of plant diversity or areas with an unusually high number of endemic species, both criteria for obtaining a greater payoff in preservation of overall biodiversity per square kilometer.

Unfortunately, the data available from herbaria is concentrated in several heavily collected sites. Furthermore, many species of plants in the humid tropics are rare in nature so that their presence in an area is only determined after many years of site-intensive field work. It is important to have a quantitative study of botanical collecting intensity in order to determine whether centers of endemism or diversity are real or possible sampling artifacts. With this information in hand we will be in a better position to judge just how useful herbarium data is as a criterion for selecting priority conservation sites. If the data are too highly biased due to uneven collecting intensity, more equitably distributed data take on a much more important role. Otherwise we run the risk of preserving only well studied sites while losing unique but poorly collected areas.

Remote sensing provides equitably distributed data for classification of vegetation physionomy and co-variate geomorphology and geology. It should be possible to produce a refined vegetation map of the Brazilian Amazon based on new technologies developed since the RADAMBRASIL project, coupled with verification at progressively larger scales in selected sites using aerial photos and a rapid standardized field inventory procedure for checking diversity, species composition and forest structure. The most recent vegetation map available (IBGE, 1988) is largely based on outdated SLAR technology of 1970, and is little more than a transposed geomorphological taxonomy which gives great emphasis to altitude and degree of erosional dissection.

2. COLLECTING INTENSITY

Ideally, botanical sampling activity should be uniformly distributed throughout the region so as to permit comparisons between sites. In order to quantify the extent to which the real sample differs from this ideal we have determined the number of collections from each of the 466 1-degree squares in the five million square km Brazilian Legal Amazon, using the widespread and commonly collected tree genus **Inga** as a sample. This group of easily identified trees is common along river banks and in secondary forests throughout the basin. Since these habitats are easiest to collect, the genus is probably taken by general collectors wherever they go. **Inga** is also an important component of dry land (terra firme) primary forests and gallery forests. We selected this taxon as one which would provide little bias and best indicate botanical collecting intensity. Nonetheless, collecting effort will probably be somewhat overestimated at some sites where **Inga** is more common. It is unfortunately not feasible to obtain a random sample of Amazonian specimens from an herbarium until the total number of Amazonian collections is known.

In 1989 we censused all specimens of **Inga** for the nine herbaria in the world holding substantial numbers of Brazilian Amazonian collections. These herbaria are identified by acronyms according to international convention: INPA (Manaus), MG (Belém), IAN (Belem), R (Rio de Janeiro), RB (Rio de Janeiro), SP (São Paulo), UB (Brasilia), NY (New York) and US (Washington). The seven Brazilian herbaria hold 3,586 **Inga** collections. The two North American herbaria hold many duplicate specimens, but only 44 collections without duplicates in Brazil. We are therefore confident that our census of just nine herbaria covers a sample representing more than 90% of all vascular plants ever collected in the region. After deleting duplicate collections we were left with a total of 2,911 different collections of **Inga** made in the Brazilian Amazon. For 2,779 of these we were able to determine latitude and longitude. In the INPA herbarium this genus represented exactly 1.0% of the 115,000 Brazilian Amazonian vascular plants incorporated into the collection as of January, 1989. We therefore estimate that slightly more than 300,000 different collections of vascular plants have been made in the region since collecting began, including the herbaria we did not census. This is the specimen base which provides all data for phytogeographers and which we submitted to analysis in our quantification of collecting intensity.

A collecting intensity map was elaborated using SURFER (1985). The data are presented in Fig. 1 as a three dimensional surface. It is immediately obvious from this map that phytogeographical sampling of the Amazon flora is highly biased toward several collecting islands, while most of the region remains poorly explored. The least studied portion of the Amazon forest is in an area suffering very high rates of deforestation: southern Pará and northern Mato Grosso. Tocantins (formerly northern Goiás) and central Mato Grosso appear

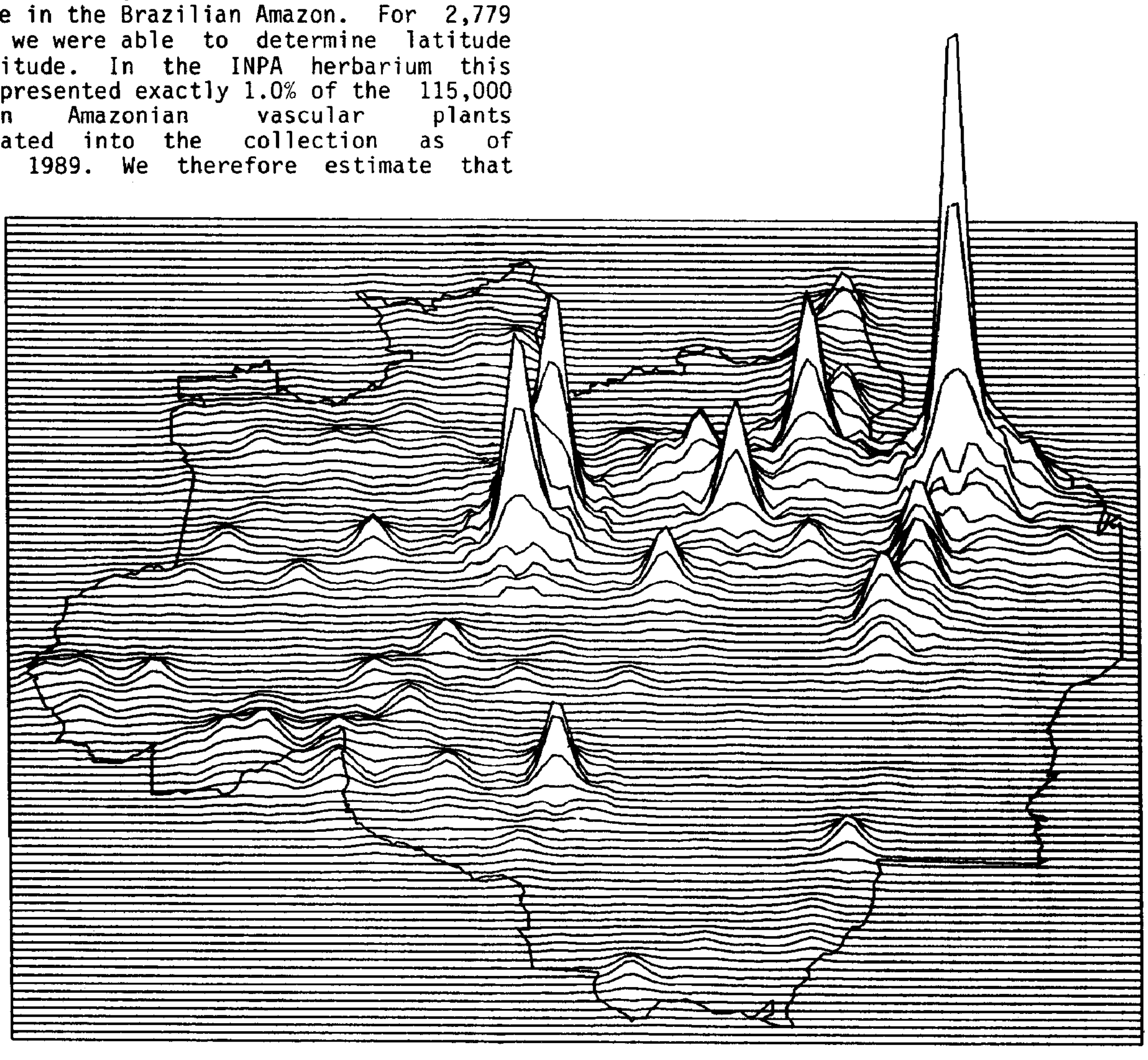

Fig. 1. Density of arborescent angiosperm collections made in Brazilian Amazonia as of 1989 based on 1.0% sample from nine herbaria (INPA, MG, IAN, RB, R, SP, UB, NY & US). Based on number of specimens of genus **Inga** per 1-degree grid square, interpolated to a 0.25 x 0.25 degree resolution to produce a finer trace. Duplicate collections deleted, leaving total sample of 2,779 specimens. See Table 1 for localities, Fig. 2 for state boundaries.

TABLE 1
BOTANICAL COLLECTING ISLANDS IN THE BRAZILIAN AMAZON
RANKED BY DECREASING COLLECTING INTENSITY

Collecting Island	Associated with Postulated Refuge? (Refuge Name)
Belém/ Tucurui/ Carajás-Itacaiunas	Yes (Belém)
Manaus/ Manaus-Itacoatiara Hwy	Yes (Manaus)
Jari/ Gurupá	No (near dry forest/ floodplain)
Santarém	No (dry forest)
Óbidos/ Trombetas	Yes (Trombetas)
Eastern Acre/ Abunã	No (close to Bolivian savannas)
Aripuanã	Yes (Rondonia/Aripuana)
Tapajós Lower Rapids	Yes (on edge of Tapajós Refuge)
Macapá	No (in or near cerrado)
Tefé	Yes (Tefe)
RGS Base Camp (E. Mato Grosso)	No (cerrado)
Lower Xingu	No (dry forest/ savanna)
Humaitá	No (savanna)
Northern Amapá	Yes (Eastern Guiana)

Note: Refugia are postulated sites of isolated humid forest during dry Pleistocene. Their delimitation requires detecting many overlapping cases of local non-edaphic endemism, vestiges of allopatric speciation in the now continuous forest. Dry forest, cerrado, savanna, white sand areas and floodplain areas are not eligible candidates for refugia.

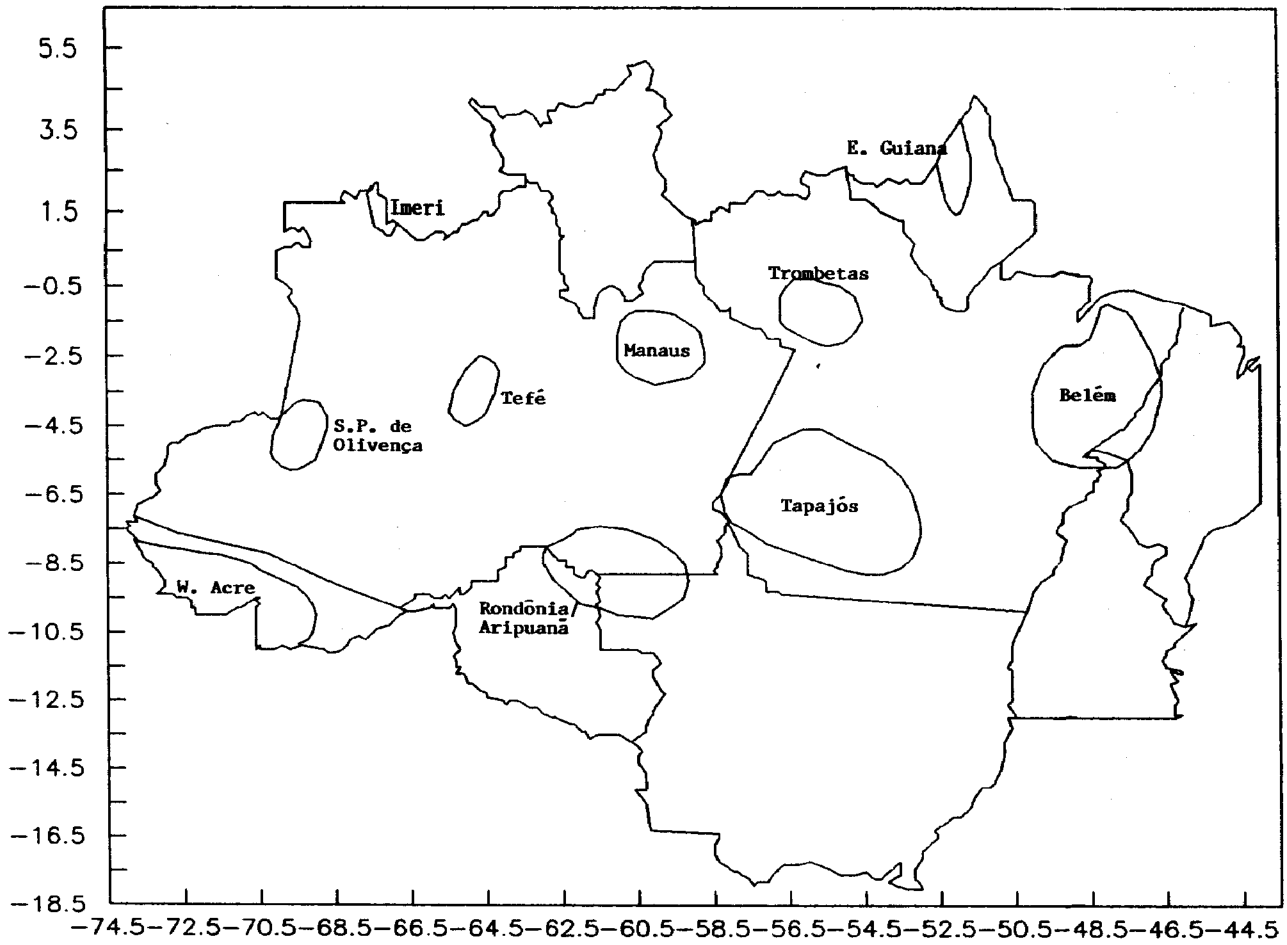

Fig. 2. Ten endemism centers, or Pleistocene refugia, postulated for Brazilian Amazonia based on study of woody angiosperms, precisely redrawn from most recent and accurate map published (Prance, 1982b, pers. comm.).

poorly collected, but this is due in part to the absence of forest, and therefore of the genus **Inga**, in this area. Nonetheless, gallery forests within cerrado regions do show up as indicated by the slight hump at Cuiaba and the larger hump in eastern Mato Grosso where the Royal Geographical Society undertook intensive collecting in the 1960s.

Table 1 shows there is a clear correspondence between collecting islands and some of the proposed botanical endemism centers -- or Pleistocene forest refugia -- proposed by earlier workers using herbarium-based evidence. Seven botanical refugia have been proposed entirely within the Brazilian Amazon and another three straddle the region's borders (Fig. 2). For the seven refugia/endemism centers within Brazilian Amazonia only the São Paulo de Olivença refuge is not associated with a collecting island and therefore not suspect of being a collecting artifact. As for the three on international borders: the East Guiana refuge is associated with a collecting center in Amapa; the Western Acre/Eastern Peru refuge may be largely based on collections from the Rio Ucayali in Peru; the Imeri refuge is based on collections from outside Brazil.

3. RARITY OF SPECIES

The problem of uneven sampling density worsens with increasing species richness and decreasing equitability in plant communities. If there are many species and many of those are exceptionally rare, local floras will appear to be more unique the more intensely they are studied. We then run an even greater risk of recommending preservation of well collected sites while neglecting poorly studied areas with more unique floras.

Low equitability in species rich humid tropical forests is well documented. On central Amazonian terra firme soils a species x area curve does not level off until about 5,000 trees have been censused. We analyzed the problem of commonness vs. rarity in the herbarium by counting the number of specimens of all Brazilian Amazonian Chrysobalanaceae in the INPA collection (Nelson et al., in press). A total of 1,971 individual specimens were distributed among 156 species. Two-thirds of the species had less than ten collections and 32 (20%) were represented by just a single collection. Plotted as a ranked histogram, there is a sharp decline in commonness followed by a very long tail of exceptionally rare species. This problem of many rare species occurs even with large samples in a small area. Hubbell & Foster (1986) censused 238,000 woody plants on 50 hectares at Barro Colorado Island, Panama. These represented 301 species, 25 of which (8%) were collected only once. Unless they are large trees, these 25 species and many others would simply never be encountered at the ordinary intensity of botanical study. Note that these 50 hectares received nearly the same sampling effort that is diluted across the entire Brazilian Amazon region (238,000 vs. 300,000 collections).

4. ROLE OF REMOTE SENSING

Unlike herbaria, satellite images can provide equitably distributed data for the entire Amazon. Obviously images alone cannot indicate plant species composition, diversity or endemism. They can, however, be used to discriminate different vegetation types, including various flood forests, dry forest, savanna and white sand areas. The end-member optimization technique being developed by Dr. John Adams holds great promise for classifying and mapping different forest canopy textures, which are related to forest biomass, frequency of emergent trees and frequency of natural tree-fall gaps. Satellite images also discriminate two co-variates of vegetation: geomorphology and geology. In the lower Trombetas area Landsat MSS imagery shows a clear correlation between forest types and the transition from Tertiary to Paleozoic substrate, as well as between different Paleozoic substrates. Influence of substrate on vegetation type is more evident in this drier part of the Brazilian Amazon, but even in wetter areas the effect of underlying Paleozoic beds is detectable in vegetation -- along the Rio Jatapu, for example -- or as geomorphic/vegetation units, as in the sandstone flora of Presidente Figueiredo or the sandstone tepui of Serra do Aracá. RADAM imagery indicates the presence of patterned white sands in the upper Guaporé, suggesting a habitat similar to the waterlogged white sands on both sides of the lower Rio Branco. The upper Guaporé in Rondônia has never been visited by herbarium collectors.

Satellite data can be of greatest use if coupled with verification at progressively larger scales. SPOT imagery, vertical stereo pairs, oblique photos from overflights and finally on the ground botanical inventories are presently available for this purpose. Spectral signatures and canopy roughness, detectable via remote sensing, can be linked to forest structure so as to permit extrapolations in mapping vegetation types. We propose the following rapid and inexpensive methodology for ground truthing vegetation units detected remotely:

1. 0.1 ha. inventories for all plants > 2.5 cm DBH. This methodology has been used in forests all over the world (Gentry, 1988) and so is the de facto standard for comparing diversity, growth habit types and to a lesser extent species composition and structure. A single sample usually includes about 400 individuals and can be completed in 3-5 days.

2. Checklist of palm species: a good indicator of forest diversity, this family can be censused more or less completely in the field in a short time by a trained person.

This is meant to overcome the species-area deficiency of the 0.1 hectare inventories.

3. Basal area per hectare for trees > 10 cm DBH: a good rapid comparator of biomass. Size class data will indicate forest structure at each site, useful for extrapolating coverage of different vegetation types identified in the imagery.

A three year pilot study of Central Amazonia is planned and will concentrate on 10-15 sites within a 130 km radius of Manaus. This area includes a great diversity of vegetation types coupled with substrate variability: unconsolidated Tertiary deltas with clay latosols and podzols; Paleozoic sandstone, shale and carbonate beds; granite shield; raised Pleistocene floodplain terraces; muddy water "várzea" floodplain; black water "igapó" alluvium; as well as finer sub-divisions within these units. A test inventory using the 0.1 hectare technique confirms the Tertiary latosols as having one of the highest diversity levels of any neotropical site, with over 200 species per 400 individuals. Remarkably, before this inventory was done only one vouchered measure of forest diversity was available for the Manaus terra firme latosols (Prance et al., 1976).

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