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Amazonian biodiversity: assessing conservation priorities with taxonomic data

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Data from 3991 records of museum collections representing 421 species of plants, arthropods, amphibians, fish, and primates were analyzed with GIS to identify areas of high species diversity and endemism in Amazonia. Of the 472 $1 \times 1°$ grid cells in Amazonia, only nine cells are included in the highest species diversity category (43–67 total species) and nine in the highest endemic species diversity category (4–13 endemic species). Over one quarter of the grid cells have no museum records of any of the organisms in our study. Little correspondence exists between the centers of species diversity identified by our collections-based data and those areas recommended for conservation in an earlier qualitative study of Amazonian biodiversity. Museum collections can play a vital role in identifying species-rich areas for potential conservation in Amazonia, but a concerted and structured effort to increase the number and distribution of collections is needed to take maximum advantage of the information they contain.

Keywords: biodiversity; Amazonia; geographic information system (GIS); museum collections; species diversity.

Introduction

One of the major challenges for environmental conservation in the next century will be the preservation of the species-rich habitats of the Amazon Basin of South America. It is clear that only a small part of the remaining forested areas can be preserved unless there is considerable change in the current social, political, and economic priorities of the region. If only a portion of these habitats can be maintained, it is imperative that areas be identified which maximize the amount of genetic diversity contained in forest reserves and protected areas.

As systematic biologists, we are concerned with understanding the extent and distribution of organismic diversity as well as using this knowledge for conservation purposes. A number of methods have been advocated for defining what constitutes areas of maximum genetic diversity. Some scientists propose using species diversity as the basic criterion (Brown, 1988); others suggest phylogenetic diversity (Erwin, 1991; Vane-Wright *et al.*, 1991; Morrone, 1994). If the first criterion is applied, both total species richness (i.e. maximizing the number of species) and endemic species richness (i.e. maximizing the concentration of rare species) are usually taken into account (Wilson, 1988; Williams *et al.*,

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1996). In order to use the second criterion, additional information concerning the evolutionary history of the taxa is required.

After 100 years of collecting data on species diversity and distribution in the Amazon Basin, we are still far from a complete understanding of where the greatest concentrations of biological diversity are located (Nelson *et al.*, 1990; Voss and Emmons, 1996). However, we believe that the existing specimen data, although incomplete, can and should be used for making certain conservation recommendations if the limitations of the data are recognized.

In 1990 a group of taxonomic specialists and conservationists made an attempt to identify conservation priority areas in Amazonia based on their individual concepts of biotic diversity resulting from field experience with various groups of organisms (Workshop '90 – Biological Priorities for Conservation in Amazonia). The resulting map (Anonymous, 1991), based on a qualitative synthesis of species diversity and endemism criteria, outlined five levels of priority areas for conservation. This effort was among the first attempts to identify such priority areas and has generated some debate within the biological and conservation communities, especially because the data used to create the map were never published.

The objectives of the present paper are: (1) to use documented taxonomic data (in the form of museum collections) from a range of representative organisms to determine areas of high species diversity and endemism in Amazonia; (2) to assess the adequacy of our current taxonomic data for correctly identifying centres of diversity; and (3) to compare our results based on collection data to the conservation priority areas recommended by Workshop '90.

Methods

We selected distributional data from various taxonomic groups found in Amazonia, e.g. plants, arthropods, fishes, amphibians, and primates. Within each of these major groups, genera were selected for which we had first-hand taxonomic expertise that guaranteed we had the best identifications possible and the most accurate locality information (latitude, longitude, and elevation). In total 3991 records of 421 species in 33 genera were included in the analysis (Table 1). A record constitutes a specific locality at which a species has been collected one or more times. These collection records provide a repeatable and reliable data set for analysing the distribution of biological diversity. Although other taxa could have been selected for the analyses, these genera exemplify a cross-section of both rare and common species found in Amazonia and represent one of the most extensive taxonomic samples currently available for this geographic region. The collections from which the distributional data were taken are housed at museums and universities throughout the world and in many cases are exhaustive for the particular species studied.

We defined the geographic extent of Amazonia according to the map of Ab'Sáber (1977). Any species with a significant portion of its distribution within the Amazonian domain (and below 350 m) was included. Most of the genera and species are restricted to Amazonia, but some have extra-Amazonian (e.g. trans-Andean, Caribbean, Central American) distributions as well. If a species met this criterion, all localities within Amazonia for that species were included in our data set.

An endemic distribution is one that is limited to a specific area within Amazonia. Numerous approaches have been used to define 'specific area' (Nelson *et al.*, 1990;

Table 1. Taxa used in the analyses of Amazonian biodiversity distribution

Taxon	No. of species	No. of records
Plants		
Heliconia	30	440
Phenakospermum	1	17
Talisia	35	198
Total for plants	66	655
Arthropods		
Agra	101	122
Batesiana	21	79
Deinopis	6	16
Geballusa	2	4
Gouleta	3	28
Hemiceras	108	342
Total for arthropods	241	591
Amphibians		
Leptodactylus	14	536
Total for amphibians	14	536
Fishes		
Boulengerella	5	112
Caenotropus	3	55
Copeina	1	25
Copella	3	38
Cyphocharax	2	6
Lebiasina	1	15
Nannostomus	15	123
Pyrrhulina	2	17
Steindachnerina	33	419
Total for fishes	65	810
Primates		
Alouatta	2	152
Aotus	3	104
Ateles	3	43
Cebuella	1	41
Cacajao	3	50
Callicebus	2	191
Callimico	1	27
Callithrix	2	58
Cebus	2	19
Chiropotes	2	108
Lagothrix	1	74
Pithecia	5	187
Saguinus	7	236
Saimiri	1	109
Total for primates	35	1399
Total	421	3991

Anderson, 1994, Morrone, 1994) and we considered several (e.g. a simple visual approach, minimum polygon maps, minimum spanning trees). We adopted a procedure that transformed latitude and longitude data for each locality into decimal format (assigning positive values to latitudes north of the equator and negative values to those south of the equator) and calculated the standard deviation for each variable for all species throughout their entire ranges both within and outside Amazonia. Endemic species distributions within Amazonia were heuristically defined as those with standard deviations for both latitude and longitude of less than or equal to 1.00. Although delineated arbitrarily, this definition allowed us to clearly quantify and compare endemic distributions within Amazonia.

Geographical information system (GIS) analyses were then carried out to determine the distribution in Amazonia of species, endemic species, and species records. The base map for the analysis was the Plate Carree projection; coastlines, rivers and political borders were derived from the Digital Chart of the World and generalized to a scale of 1:25 000 000. Ab'Sáber's (1977) Amazonian Morphoclimatic Domain boundary, chosen as the consistent limit for species' analyses in the Basin, was digitized and transformed to fit the base map projection. Grid cells of one degree on a side were prepared for Amazonia. This border was then used to clip out any specimens that fell beyond it; data in any grid cells that straddled the line were accordingly partitioned. Point maps of individual species were produced through the conversion of either ASCII or dBase formatted data sets of longitude and latitude (given in degrees and minutes) to decimal degrees. Data bases were then attached to each of the species map layers. All points with their associated data bases were then joined together for easier analysis using Boolean operators. A data base for each cell was built containing: (1) the number of species; (2) the number of endemic species; (3) the number of records; and (4) for plants the number of collections per species. From this data base, choropleth maps of all four data fields were created. Numerical classing of the data was conducted using the CLASSY program (Moore *et al.*, 1988) that enables one to minimize variance within classes and maximize variance among classes. The high priority areas of the Workshop '90 map were then overlaid for comparison with the taxonomic data.

The relationship between numbers of species and numbers of endemic species per grid cell was determined for all combined taxa using a correlation analysis. To determine the relationship between species number and collection intensity we used all the collections for a species and not just localities in a subset of our data (plant taxa; 702 total collections) in a regression analysis between the number of species and (1) the number of collections, and (2) the number of collections per species per grid cell. Grid cells lacking any collections were omitted from the analyses.

Results

The distribution of species across all taxa within the 472 one-degree grid cells in Amazonia comprise six categories between 0 and 66 species per grid cell (Table 2; Fig. 1). Over one quarter of the grid cells had no representative species of the groups under study, i.e. no collections. Only 2.0% of the total grid cells had high species diversity (45–66 species) and 57.8% had low species diversity (1–11 species). The nine areas with highest diversity are scattered throughout the region (Fig. 1) and in general correspond to well-known and historical collection localities (e.g. Tambopata Reserve, lquitos, Tefé, Manaus, Cayenne,

Table 2. Distribution of Amazonian diversity for all taxonomic groups studied

Unit of diversity	No. of grid cells	% of Total grid cells in Amazonia	No. of grid cells in Workshop '90 high priority areas	% of Total grid cells in Workshop '90 high priority areas
Species				
0	129	27.3	24	20.0
1–4	186	39.4	46	38.3
5–11	87	18.4	17	14.2
12–37	61	12.9	30	25.0
45–53	5	1.1	2	1.7
63–66	4	0.9	1	0.8
Endemic species				
0	408	86.4	96	80.0
1	40	8.5	16	13.3
2–3	15	3.2	4	3.3
4–7	5	1.1	2	1.7
9–11	2	0.4	2	1.7
13	2	0.4	0	0.0
Records				
0	129	27.3	24	20.0
1–8	225	47.7	54	45.0
9–27	78	16.5	25	20.8
28–52	26	5.5	12	10.0
56–91	13	2.8	5	4.2
143	1	0.2	0	0.0

etc.; Table 3). There is no obvious species diversity gradient between east and west or north and south.

With respect to numbers or records, individual grid cells ranged from 0 (129 cells) to 143 records (1 cell; Table 2; Fig. 2). Of the grid cells with records present 64.2% had 27 or fewer records per grid cell. The remaining 40 grid cells with more than 27 records had an average of 49.3 records per cell. If individual taxonomic groups are considered separately, insects are the least collected with nearly 84% of grid cells with zero records and primates are the most evenly sampled with over 53% of the grid cells with at least one record.

According to our criterion for identifying endemic species, 64 grid cells in Amazonia contained from 1 to 13 endemic taxa (Table 2; Fig. 3). Nine areas comprised the three highest categories (4–13 endemic species; Table 3); the remaining 55 grid cells contained from one to three endemic species. Five of the nine grid cells with the highest endemicity corresponded to areas with the highest species diversity (45–66 species). The overall distribution of endemic species was significantly correlated with the distribution of total species number ($r = 0.634$; $n = 343$; $p \ll 0.001$).

In the separate analyses of only the plant taxa that included all collection data, collection depth (i.e. collections per species) in Amazonia is exceptionally low even though some of the species are conspicuous and common (e.g. *Heliconia*). Although there were no records for 63.3% of the grid cells, in the remaining grid cells with collections, 26.7% of total (126 cells) had only one collection per species, 8.3% (39 cells) had between one and

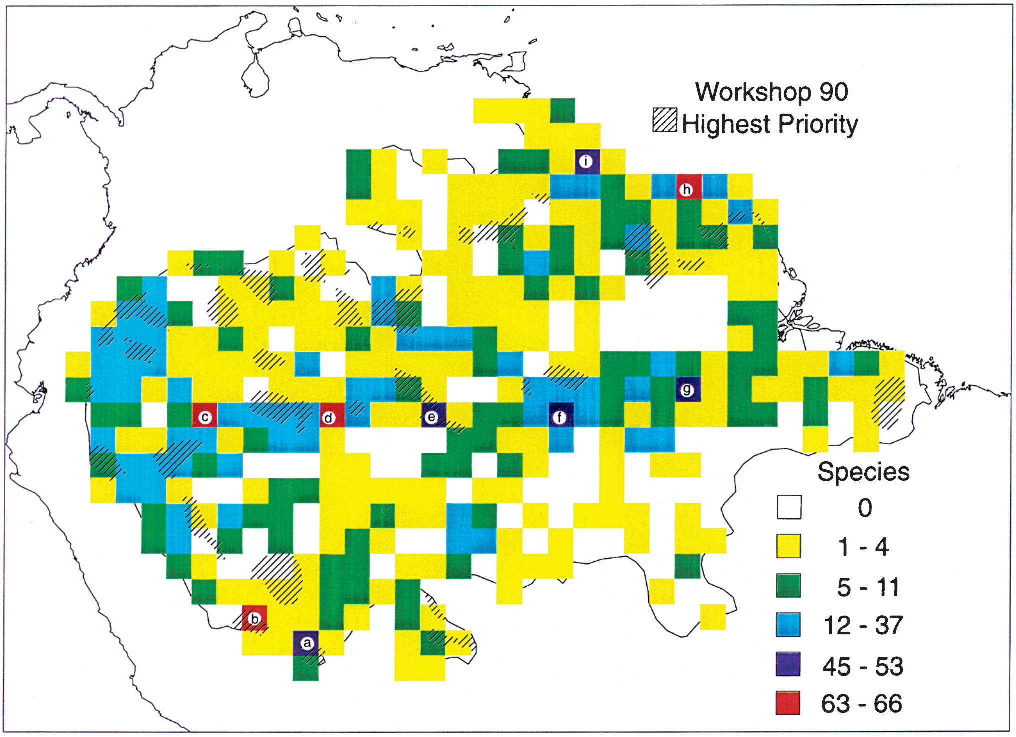

Figure 1. Geographic distribution in Amazonia of species diversity for all taxa combined. The number of species is indicated for each of the 472 1 × 1° grid cells. The Workshop '90 high priority conservation areas are also shown. Grid cells with the highest number of species are indicated by lowercase letters (for localities see Table 3).

Table 3. Areas (grid cells) with highest species diversity (43–67 species; marked with *) and highest concentrations of endemism (4–13 endemic species; marked with ‡) in Amazonia. Identifying letters correspond to grid cells marked in Figs 1 and 3

Identifying locality within grid	Latitude, longitude (NW corner of gird cell)
a. Tambopata, Peru*	12°S, 70°W
b. Cocha Cashu – Manu, Peru*‡	11°S, 72°W
c. Iquitos, Peru*	3°S, 74°W
d. Along upper Rio Solimões, Brazil*‡	3°S, 69°W
e. Tefé, Brazil*‡	3°S, 65°W
f. Manaus – Ducke Reserve – INPA, Brazil*	3°S, 60°W
g. Santarém, Brazil*	2°S, 55°W
h. Parimaribo Region, Surinam*‡	6°N, 55°W
i. Georgetown, Guyana*‡	7°N, 59°W
j. Cayenne, French Guiana‡	5°N, 53°W
k. Moyobamba, Peru‡	6°S, 77°W
l. Río Ucayali, Peru‡	5°S, 75°W
m. Porto Velho, Brazil‡	8°S, 64°W

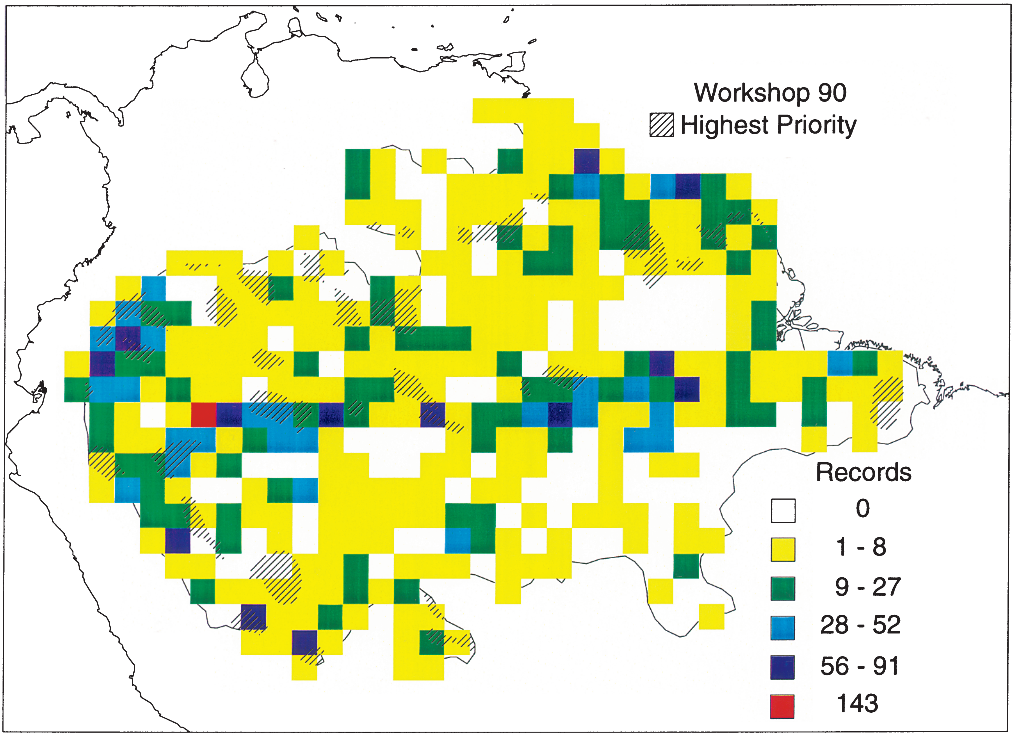

Figure 2. Geographic distribution in Amazonia of collection records for all taxa combined. The number of records is indicated for each of the 472 $1 \times 1°$ grid cells. The Workshop '90 high priority conservation areas are also shown.

two collections per species, and 1.7% (8 cells) had between 2.3–7.0 collections per species. In the latter areas with the greatest collection depth, five grid cells had high species diversity (6–15 species) and three had low diversity (≤5 species). Of the total 23 grid cells with the highest plant species diversity (6–15 species), 18 cells had fewer than two collections per species. The number of species was highly dependent on the number of collections made in any grid cell ($r = 0.919$; $p \ll 0.001$), but not so with respect to collection depth ($r = 0.310$; $p < 0.01$).

The lack of correspondence between the high priority areas of the Workshop '90 report and our data is striking (Table 2; Figs 1–3). Only 25.3% (120 grid cells) of the total area of Amazonia overlaps in part with the Workshop '90 high priority areas. The highest species areas (45–66 species) identified by our data correspond with only 2.5% of the Workshop '90 high priority areas, whereas 52.5% of their priority areas have low species diversity for the taxa we studied (less than 11 species). Furthermore, 65.8% of the grid cells in high priority areas are represented by 27 or fewer collections records and 20% of the Workshop '90 high priority grid cells are represented by no records at all in our sample. Of the nine highest areas of endemicity identified by our sample, only four fall in the high priority areas of Workshop '90; the two grid cells with the highest endemicity (13 endemic species) were not included within the high priority areas of Workshop '90.

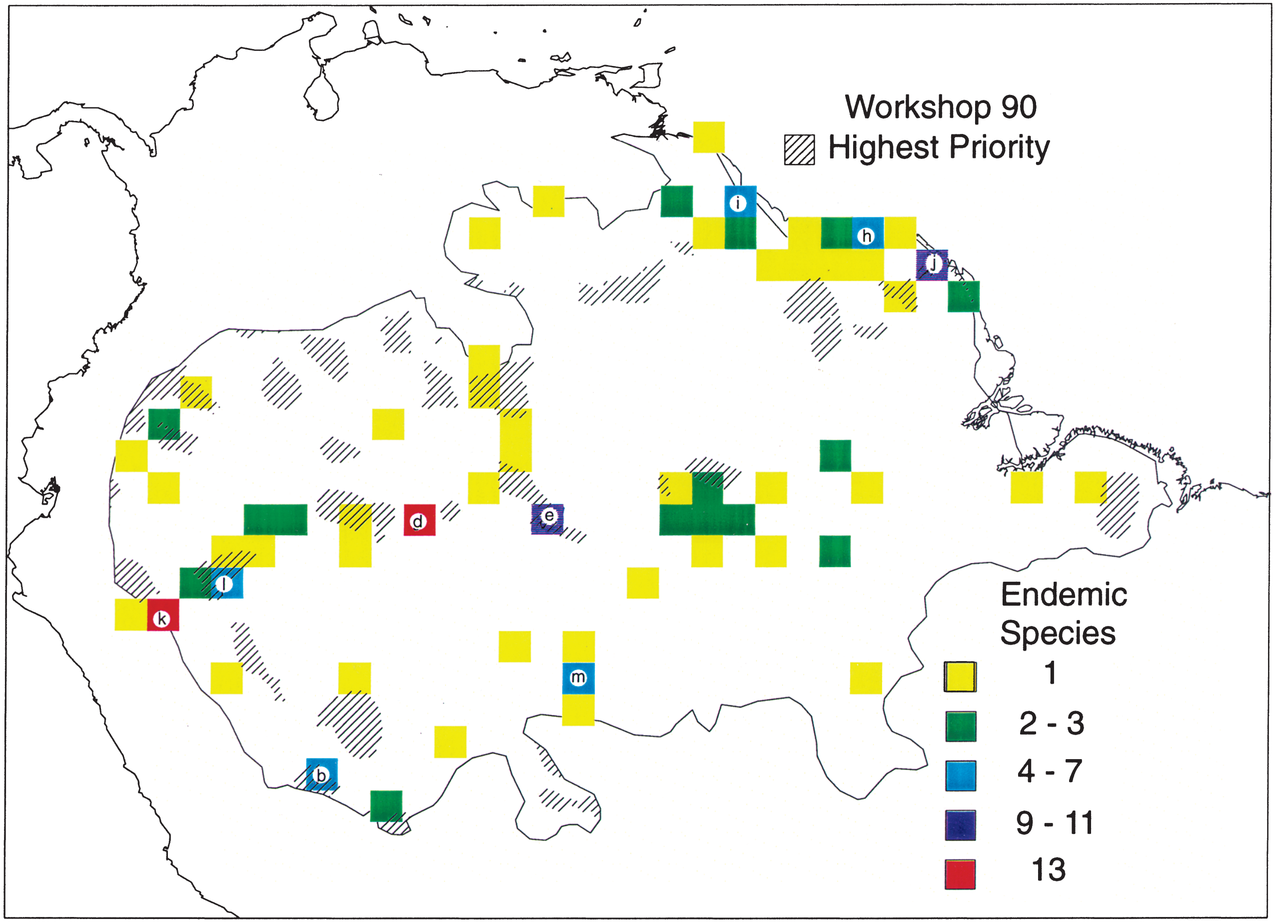

Figure 3. Geographic distribution in Amazonia of endemic species diversity for all taxa combined. The number of endemic species is indicated for each of the 472 1 × 1° grid cells. The Workshop '90 high priority conservation areas are also shown. Grid cells with highest concentration of endemic species are indicated by lowercase letters (for localities see Table 3).

Discussion

To understand the implications of our results, it must be remembered that the genera and species included here are exemplars of most of the major groups of macro-organisms found in Amazonia (i.e. plants, arthropods, fishes, amphibians, and primates) and do not constitute an exhaustive survey of the biota of the area. Such exhaustive surveys of taxa are not available. We also recognize that the Amazonian region is a heterogeneous composite of different habitats and that some of our taxa are habitat specific (e.g. *Talisia* found primarily in non-flooded wet forest and not savannas or open vegetation) and therefore do not have an equal probability of occurring in each grid cell. Nonetheless, our collection data represent one of the most complete compilations of distributional information currently available for making generalizations on geographic patterns of biodiversity in Amazonia. The only comparable data sets are for birds and several groups of butterflies and plants (Haffer, 1969; Prance, 1982; Brown, 1987). As additional taxa are added to analyses such as ours, concepts of centres of diversity and priority areas for conservation will be refined.

The centres of high diversity identified with our data (Fig. 1; Table 3) not surprisingly correspond to many of the major 'hot spots' that historically have been the focus of museum collectors over the years, e.g. areas around Iquitos, Manaus, Santarém, and Cayenne (Nelson *et al*., 1990). The nine highest species grid cells (45–66 species) in Amazonia all correspond to the most intensively collected areas (56–143 species records). If the total number of species is accepted as the central criterion for determining genetic diversity, one might recommend that the top nine most diverse regions identified here, and especially those five areas that overlap with high levels of endemism (Table 3), be considered as high priority areas for conservation. However, at this time we cannot make such a recommendation for the reasons outlined below.

We can identify no areas in Amazonia that have been thoroughly sampled or even adequately sampled in most cases for all organismal groups. The results of both the mapping of the plant collection data and the regression analyses indicate that the perceived species diversity of any area in Amazonia is a direct function of how many collections have been made in that area and not necessarily the absolute level of diversity. If the plant data are representative of collections of most organismal groups (and we believe they are), then very few localities have more than a single collection per species even in the areas with high numbers of collections. It is therefore likely that all areas will prove more diverse when additional collections are made. The shallow collection depth for most of Amazonia underscores the paucity of collection data available for making biological generalizations or conservation recommendations. It is discouraging that even after a century of inventory and collecting efforts adequate distributional data are lacking for most organisms. More discouraging is the absence of any current plan to intelligently sample Amazonia.

Of the 13 highest diversity localities, six (Tambopata, Iquitos, Tefé, Manaus, Santarém, and Georgetown) represent high diversity areas for all of the five main groups of sampled organisms. Our data also indicate that where arthropods have been adequately sampled, they disproportionately contribute to the high levels of diversity, especially with respect to endemicity (e.g. Cocha Cashu, Upper Rio Solimões, Parimaribo, Porto Velho). Nonetheless, it is encouraging that some of the taxonomic groups sampled here (e.g. plants, frogs and primates), even though their overall distribution is still unknown, are relatively well understood taxonomically because they have been sufficiently sampled in at least some areas of Amazonia (Heyer *et al*., in preparation).

Workshop '90 represented an impressive cross-section of individuals with extensive expertise in organismal distributions and conservation strategies in Amazonia. Their recommendations for high priority conservation areas were founded on both a knowledge of biologically explored areas as well as unexplored regions of Amazonia. Our museum-based collection data support the recognition of at least a subset of their high priority areas as regions of exceptional biodiversity. However, our study also indicates that the majority of the high priority areas lack significant collection data to verify their recommendations. As such, the Workshop '90 map should be treated as a hypothesis of centres of Amazonian diversity and not as a conservation planning document. It is probable that other more poorly explored areas of Amazonia, some of which are identified on the Workshop '90 map, will prove to have higher diversity than the areas identified in our study. However, we believe that areas of high diversity which are documented with collection data should be given conservation priority over areas of suspected diversity, but which lack supporting collection-based data. Reliable taxonomic data provide a baseline upon which convincing and achievable conservation recommendations can be formulated.

Finally, we emphasize that our data represent total numbers of species recorded from a particular area and do not address the 'quality' of those species. Some investigators have pointed out that absolute numbers are not the best gauge of genetic diversity and that other criteria, such as phylogenetic uniqueness and position (Erwin, 1991; Vane-Wright *et al*., 1991), concentrations of endangered taxa (Dobson *et al*., 1997), or richness of indicator taxa (Prendergast and Eversham, 1997), are better measures for conservation purposes. Additional biological information about species, which can be provided by systematists, field biologists, and local naturalists, also must be taken into account when identifying high diversity regions. We describe elsewhere (Heyer *et al*., in preparation) how our data can be used in conjunction with such information to address conservation issues.

In summary, analyses of biological data derived from museum collections provide predictive tools for identifying critical biodiversity regions for conservation. Yet the acquisition of biological information is only the first step in a many-tiered process of determining conservation areas for protection that includes social, political and economic factors as well. In order to take this first step it is clear that our current knowledge of the distribution and diversify of the biota in Amazonia must be greatly expanded. A renewed and structured effort to inventory with vouchered collections the various habitats of Amazonia is imperative if we are to make informed decisions on conservation priority regions in the near future.

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