AMAZONIAN NATURE RESERVES: AN ANALYSIS OF THE DEFENSIBILITY STATUS OF EXISTING CONSERVATION UNITS AND DESIGN CRITERIA FOR THE FUTURE

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SUMMARY

Many tropical nature reserves are woefully understaffed or exist only on paper. Without effective implementation, tropical reserves cannot count on *in situ* enforcement, and consequently are subject to a wide range of invasive threats. Weak institutional structures are aggravated by reserve designs which facilitate rather than discourage unlawful human activities.

Here we begin with the assumptions of severe financial and institutional constraints and then consider the current status of forest reserves in lowland Amazonia. We ask how the criteria by which reserves are delimited may affect the efficiency with which the contained areas can be defended under these assumptions. In a GIS analysis, we find that 40% to 100% of the area of all existing nature reserves in Brazilian Amazonia is directly accessible via navigable rivers and/or functional roads. Such access greatly facilitates the illegal offtake and conversion of forest resources in a region where each guard is responsible for protecting an area larger than the State of Delaware.

Cost effective defense of large areas can be achieved through appropriate delimitation of reserves along watershed divides and by efficient deployment of limited infrastructure and personnel. Given current and probable future levels of financial resources allocated to reserve maintenance in Amazonia, any new nature reserves in this region should be designed and sited so as to maximize their defensibility. Siting considerations based on biological criteria, such as presumed centers of diversity and endemism, should be complemented by defensibility criteria.

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INTRODUCTION

Tropical forest nature reserves are experiencing mounting human encroachment, raising concerns over their future viability even in remote areas. Long-term maintenance of nature reserves in economically marginal areas of the tropics is particularly problematical; in these areas protection is based on severely restricted funding from politically and administratively weak governments. Consequently, many tropical forest reserves operate on skeletal budgets, are chronically understaffed, lack the most basic infrastructure, and cannot count on effective institutional support in enforcing conservation legislation. Such frailties render them susceptible to a wide range of illegal activities - poaching, fishing, logging, mining, land clearing - carried out by both individuals and corporations. Worse, the frequent inability of guards, who are often unarmed and lacking authority to make arrests, to prosecute violators leads to a general disregard of reserve boundaries and regulations. Once it is observed that the responsible authorities are unable to intervene, large scale invasions of colonists, poachers, loggers, or miners may ensue, jeopardizing a reserve's biological resources.

The Amazon basin consists of some 7.05 million km^2 of lowland tropical forest in contiguous parts of Brazil, Peru, Ecuador, Colombia, Bolivia, Venezuela, and the Guianas (Irion 1978). Siting of nature reserves in this region has been profoundly influenced by biogeographic analyses purporting to locate centers of diversity and endemism for a number of plant and animal taxa (Haffer 1969; see also Prance 1977, 1982; Whitmore & Prance 1987). Reacting to newly available biological information, Wetterberg and coworkers (1976) produced the first comprehensive proposal for establishing conservation areas in Amazonia, recommending 30 high-priority areas for preservation. Proposed conservation areas coincided with centers of endemism identified by overlaying distribution maps for birds, lizards, butterflies and woody-plants (Haffer 1969; Vanzolini 1970; Prance 1973; Brown 1975). Recently, this approach was reinforced and expanded by an international workshop ("Biological priorities for conservation in Amazonia", Manaus, Brazil, January 1990), which proposed 94 priority conservation areas for the Amazon Basin (Conservation International 1991). Many criteria were incorporated in the analysis, including phytogeographic regions, centers of biodiversity and endemism, and types of soils and climate (Rylands 1990a). The resulting map has been made available to planners, politicians, and conservationists.

The maps prepared by these conservation plans have led to the establishment of nearly a score of new nature reserves. Among the first were 10 in Brazilian Amazonia resulting directly from the proposals by Wetterberg et al. (1976, 1981; see reviews in Padua & Quintão 1984; Foresta 1991). More recently, the Manaus Workshop sparked the creation of 8 Ecological Stations, which were decreed by the Brazilian State of Amazonas to coincide with proposed high-priority conservation areas (C. Miller, pers. comm.). Moreover, a comprehensive environmental blueprint entitled "Ecological and Economic Zoning of Amazonia", which carefully considers proposals from this workshop, is being prepared by Brazilian government agencies. When implemented, the blueprint is likely to have sweeping implications for Amazonian conservation, both within and outside Brazil.

To date, the biogeography of a limited number of taxa has been the primary consideration in identifying priority areas for conservation in Amazonia. Criteria of efficiency and effectiveness of protection have hardly entered the planning process (see Foresta 1991, pp. 131). Ignoring such practicalities in the design of new reserves risks defeat, for the resources available to implement and maintain a reserve may pale before the threats that have to be repulsed.

We urge that henceforth criteria of defensibility be incorporated into the process of designing and selecting Amazonian nature reserves so as to discourage, and even deter, external pressures. We suggest that in addition to biological considerations, reserve design in Amazonia should take into account the realities of low-budget implementation and weak or non-existent enforcement of conservation policy. We do not propose any specific areas for protection, such as those recommended on the basis of intrinsic biological criteria (e.g. Terborgh & Winter 1983; ICBP 1992). Rather, we focus on the pragmatic issue of how to design and site reserves so as to minimize implementation costs and maximize defensibility against existing and future external threats.

We begin our analysis with an overview of the numbers, sizes, and types of conservation units in Amazonia. We next consider practical design criteria, such as reserve configuration and location of boundaries with respect to avenues of access– especially roads and navigable rivers. We then suggest criteria for maximizing the defensibility of protected areas, given the assumption of meager investments in infrastructure and human resources. Finally, we propose some practical guidelines that could be applied in designing future Amazonian reserves.

METHODS AND DEFINITIONS

Data on Amazonian parks were obtained from published and unpublished reports of Amazonian natural resource agencies (see Instituto Brasileiro do Meio Ambiente e Recursos Naturais Renovaveis [IBAMA] 1990; Dias et al. 1991) and international non-governmental organizations (Rylands 1990b, 1991; WCMC 1992a, 1992b). Using a digitizing table (Kurta XLC 3648) and a desktop Geographic Information System (Atlas 1990), uniformly scaled maps of reserves were prepared for the Amazonian region of each Amazonian country to obtain measurements of total areas and perimeters. GIS-derived area measurements, when regressed against the areas of 50 reserves for which data were available, accounted for 99.8% of the variation, affirming the accuracy of the GIS procedure.

In a separate analysis based on 1:250,000 maps (Projeto Radam Brasil [RADAM] 1973-1981), we classified the geographic positions of existing reserves in Brazilian Amazonia relative to the total length of the watershed in which they are embedded. Watershed length was calculated using digitized linear measurements (broken down into 10-km segments) of the principal open-water fluvial course draining a reserve, from its headwaters down to its final confluence with the Amazon (= Solimões) river. Meandering of river channels was ignored because the maps we used indicate pronounced differences in river linearity across Amazonia. Reserves were then assigned to one of four categories of position along the principal watercourse (lower, central–lower, central–upper, and upper), depending on where their geometric centers fell with respect to watershed length.

In the context of Brazilian Amazonian reserves, we measure accessibility to illegal incursion as a function of non-linearized lengths of navigable rivers (open water visible from space) and roads traversing or forming the boundaries of reserves, as resolved by the best available maps for the region (RADAM 1973-1981; DMAAC 1966-1989; CIMI 1986). Our measure of accessibility assumes that (i) extraction of forest products (game, timber) in Amazonia is limited by transportation, and (ii) that most rivers and roads within reserves are accessible to unauthorized intruders. We further assume that hunters will be willing to walk up to, but not more than, 10 km from the nearest navigable river or road to extract forest products, and accordingly, we designated as accessible all such portions of reserves. The 10 km criterion is based on our own field experience and information obtained from tribal and non-tribal Amazonians (Terborgh et al. 1986; Peres 1990). For instance, a 10-km walk is often reported as the maximum hunting radius for highly profitable game, such as tapirs (*Tapirus terrestris*), in unflooded (*terra firme*) forest (Bodmer et al. 1990; pers. comm). Moreover, 10 km matches the recommended strip width for proposed buffer zones to be placed around Amazonian conservation units (Wetterberg et al. 1976; Decree 99.274/6th June 1990, National Environmental Council).

One potential weakness of our measure of accessibility is that it overlooks the large variation in human densities around reserves and associated differences in intensity of land use and intrusion pressure, all of which are subject to change over time. But in any case, the 10 km criterion applied here is likely to be conservative because it neglects the potential for canoe traffic at high water on myriad forest streams that course underneath a closed canopy and hence are invisible in the RADAM side-scanning images.

Our classification of conservation units follows that of IBAMA, the Brazilian Institute of Environment and Renewable Natural Resources (Nogueira-Neto & Carvalho 1979; Instituto Brasileiro de Desenvolvimento 1988; IBAMA 1991; Dias et al. 1991), with some slight modifications. We wish to emphasize the distinction between strict nature reserves and other types of conservation units that legally permit various forms of resource extraction. Here, "nature reserve" is used for areas set aside for absolute or nearly absolute protection of representative biotas and ecosystems. Nature reserves, including national parks, biological reserves, and ecological stations, are established for non-consumptive purposes, are strictly protected by law, and impose severe restrictions on human activities.

"Production reserves", comprising national forests, extractive reserves, and game reserves, are defined as conservation units subject to forest and game management, and are intended for "sustainable production" of timber and non-timber products. State or federal concessions to extract resources may be granted either to private interests, such as timber companies, or to communities of non-tribal Amazonians operating independently or through cooperatives.

Lastly, "indigenous reserves" are distinguished as a third category because they exist on a substantially different legislative basis (Davis & Wali 1993). Indigenous reserves in Brazil are typically administered by an independent government agency, the National Indian Foundation (FUNAI). The category includes both indigenous and anthropological reserves (Brazil), indigenous reserves and *resguardos* (Colombia), and designated Amerindian lands (Guyana).

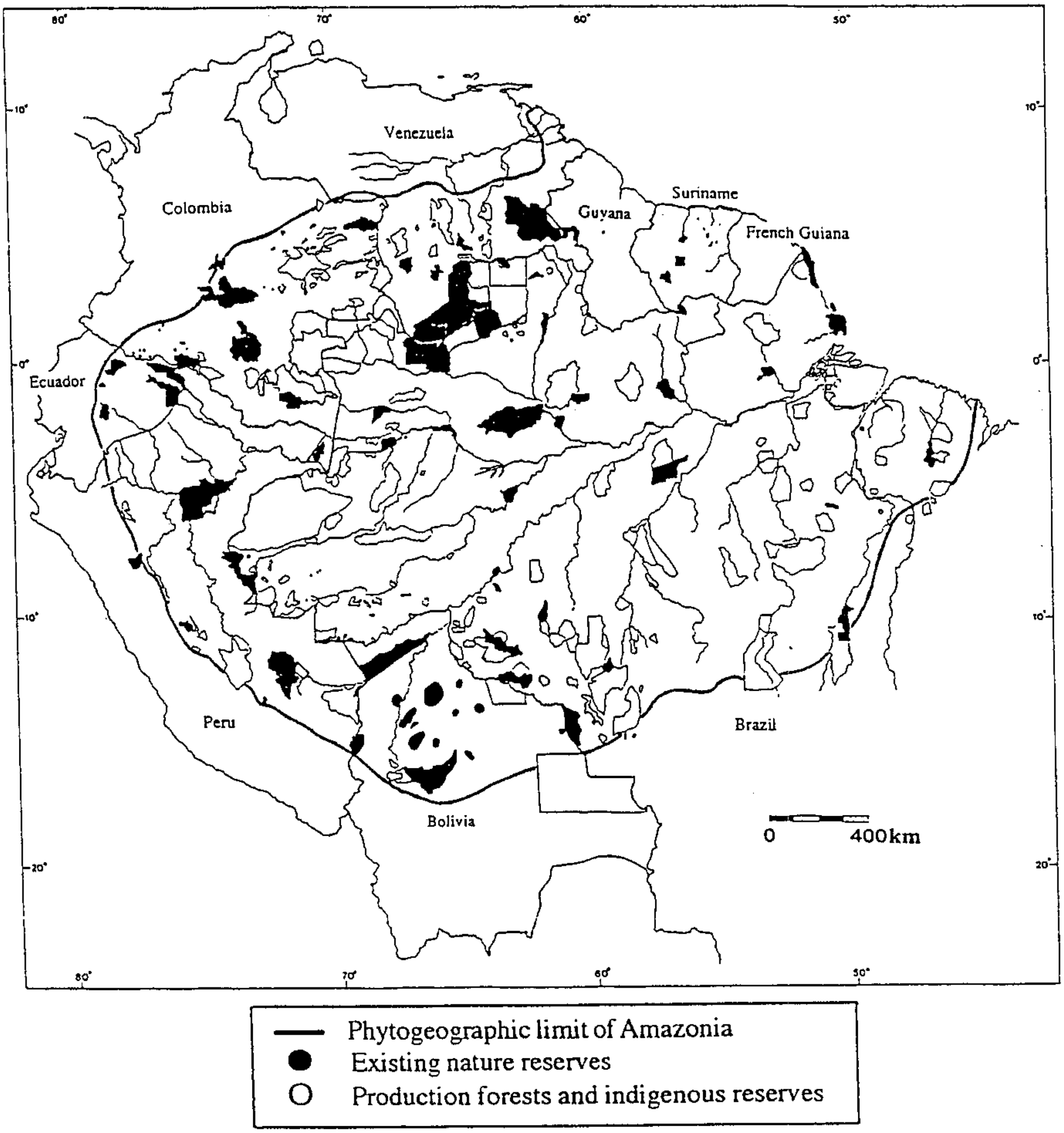

Figure 1. Geographic distribution of conservation units in all 9 Amazonian countries. The peripheral solid line indicates the phytogeographic (rather than political) limits of Amazonia. Solid areas indicate existing nature reserves. Open areas indicate production forests and indigenous reserves. Boundaries between contiguous conservation units may not be shown in every case.

RESULTS AND DISCUSSION

Existing Conservation System in Amazonia

An extensive network of 459 nature, production, and indigenous reserves has already been designated on paper in all Amazonian countries, although many of these have yet to be formally decreed (World Conservation Monitoring Centre 1992). Reserves are widely distributed across the region, although many important gaps remain to be filled (Fig. 1). Nearly half (47%) of all designated reserves are smaller than 1,000 km^2. Conservation areas between 1,000 and 10,000 km^2 account for another 41%, and those larger than 10,000 km^2 account for the remaining 12% (Fig. 2). Nature reserves have an average area of 4,765 km^2 (sd= 7,815 km^2, range= 0.1–57,740 km^2, N=117) and in general tend to be larger than production forests (mean= 3,626 km^2, sd= 5,823 km^2, range= 0.4–37,900 km^2, N= 94) and indigenous reserves (mean= 4,003 km^2, sd= 9,870 km^2, range= 0.5–83,380 km^2, N= 248).

One quarter (117 of 459) of all Amazonian conservation units are nature reserves, and theoretically have comprehensive protection. These account for 41% of the region's total acreage under some form of institutional protection. The remaining conservation units include 94 production and 248 indigenous reserves, which respectively account for 15% and 44% of all non-private land with some degree of protection.

Extensive systems of indigenous reserves are retained primarily by Colombia and Brazil. Over 18 of the 38 million hectares of Colombian Amazonia are allocated to indigenous groups. In Brazil, approximately 20% of the Amazon area consists of indigenous reserves under the jurisdiction of FUNAI. The future value of these areas for biodiversity preservation is debatable, as several Brazilian tribes have already begun a process of outright liquidation of their resource capital (Redford & Stearman 1993). Resource depletion has taken the form of large land concessions granted to logging companies and goldminers, as well as small-scale leases of forested land for a variety of exploitative uses (Economist 1993). If indigenous areas are to serve as stable strongholds of biological diversity, current practices will need to be revised and replaced by enforced limits on the rights of indigenous peoples and colonists to "manage" forest resources (Peres in press).

Conservation planning is well developed on paper in all Amazonian countries other than Suriname and Guyana, but in practice nature reserves are often lacking adequate protection. For example, only 10 of 30 nature reserves in Brazilian Amazonia have even a single local guard (Rylands 1991). Although IBAMA maintains an extensive network of administrative outposts in small towns, the locations of these offices are often far removed from the nearest reserve. Current *in situ* staffing results in an average of 1 park guard per 6,053 km^2 of nature reserve. To put this in perspective, the density of guards in the 367 units of the US National Park System is more than 70 times as great (Table 1).

Understaffing is a consequence of a low governmental priority placed on conservation needs which results in severe financial constraints, aggravated by inflated administrative structures and competition with politically stronger government sectors (see Foresta 1991 for historical review of political commitment on conservation in Amazonia). But apart from the financial and staffing limitations of park agencies, Amazonian park guards lack power to arrest violators and receive little or no backing from local police forces. Even if all these hurdles are surmounted, enforcement efforts must be pursued in a procedural vacuum without the benefit of legal precedents. Enforcement of protective legislation is therefore almost nonexistent throughout the region, and nature reserves of Brazilian Amazonia are consequently experiencing a wide range of anthropogenic threats to biodiversity (Table 2).

A lack of financial and political will can lead to abandonment of conservation units as soon as conflicts with larger economic interests arise. Some examples are: (i) central-government decisions to overrun existing reserves with road construction and settlement projects throughout the southern flank of Brazilian Amazonia (Fearnside & Ferreira 1984); (ii) plans to exploit 12 established conservation areas in Bolivia; and (iii) encroachment of national parks by petroleum and mining companies in Ecuador (WCMC 1992a, 1992b). In several of the worst cases, nature reserves have suffered from unencumbered disturbance to such a degree that they have been legally downsized or degazetted within a few years of establishment (WCMC 1992b).

Many of the human threats confronted by nature reserves could be reduced if reserves were designed and sited as to maximize their defensibility under difficult financial conditions. In practice, reserves can be protected from hunters, loggers, miners, and other illegal intruders by physical inaccessibility as well as by strategic deployment of personnel. Next, we examine the accessibility of protected areas in lowland Amazonia, as illustrated by nature reserves in Brazil.

Reserve Area vs. Perimeter

Circles minimize perimeter length per unit of enclosed area, and have consequently been proposed as optimal shapes for reserves (Wilson & Willis 1975). The size of existing nature reserves in Amazonia is a good predictor of perimeter length, explaining 90% of its variation ($r=0.951$, $N=63$). The same is true for top-priority conservation areas proposed by the Manaus meeting ($r=0.955$, $N=62$), even though the size range of these areas is nearly six-fold greater than that of existing reserves (Fig. 3).

A considerable expenditure on patrolling and surveillance effort would be required should reserve perimeters be equally accessible. We

Table 1. Comparison of the level of personnel and resources allocated to defense of nature reserves in Brazilian Amazonia and in the United States.

	Brazilian Amazonia[1]	USA[2]
In situ parkguards deployed[3]	23	4002
All nature reserve personnel[4]	65	19000
Number of nature reserves	29	367
Protected area (km^2)	139222	326721
Parkguard : area ratio	1 : 6053	1 : 82
Park personnel : area ratio	1 : 2142	1 : 17
% of reserves equipped with at least one:		
Parkguard	31	100
Administrative building	45	100
Guardpost	52	100
Motor vehicle[5]	45	100

[1] Includes all federal National Parks, Biological Reserves and Ecological Stations and Reserves (IBDF 1988; IBAMA 1990; Rylands 1991).

[2] Includes all National Park System Units (US National Park Service, pers. comm.).

[3] Includes all seasonal and full-time law-enforcement officers and rangers.

[4] Includes all seasonal and full-time parkguards, technicians, caretakers, drivers, as well as urban-based administrators.

[5] Includes aluminum canoes with outboard engines, jeeps, and pick-up trucks.

Table 2. Categories of current threats to biodiversity faced by 29 federal and 1 state nature reserves in Brazilian Amazonia (modified from Rylands 1990*b*, 1991).

	National Parks[1]								Biological Reserves[2]								Ecological Stations (or Reserves)[3]													
Types of threats	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
<u>Preventable with improved design</u>																														
Encroachment by squatters	•	•	•	•	•	•	•		•	•	•	•	•	•	•		•	•			•	•	•		•	•	•			•
Slash-and-burn agriculture												•	•	•				•		•		•								
Subsistence/commercial hunting	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Other commercial uses of wildlife					•	•			•			•	•								•									•
Commercial fishing					•				•	•	•	•	•						•					•			•			•
Selective logging	•	•	•	•	•				•	•	•	•	•	•	•			•		•		•		•			•			•
Indian reserves within boundaries	•	•	•	•	•			•						•				•												
Indian reserves along boundaries	•	•	•	•	•		•	•		•		•	•	•	•		•		•			•			•					
Goldmining	•	•	•	•	•						•							•	•			•					•			
Mining (bauxite, cassiterite)				•					•	•				•																
Agrochemical/mercury pollution	•	•		•					•		•			•					•							•	•			
Livestock conflicts	•	•	•		•				•		•		•	•							•	•			•					
Deforestation	•		•	•	•				•	•	•		•	•					•			•		•		•	•			
Tree monocultures											•																			
Soil erosion			•											•																
Episodic wildfires	•								•		•		•	•					•			•	•			•				
Heavy river traffic	•	•		•		•	•		•	•		•	•			•	•	•		•				•		•	•		•	•
Land-tenure problems	•	•	•	•	•	•	•	•	•		•	•	•	•	•	•						•				•	•			
<u>Unpreventable with improved design</u>																														
Inadequate management	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Road-building operations	•	•	•	•			•			•			•														•			
Adjacent land development	•		•	•					•	•			•	•	•	•										•		•		
Hydroelectric development									•	•						•							•				•			
Military activity				•																										

[1] <u>National Parks</u>: 1- Araguaia, 2- Amazônia, 3- Pacaás Novos, 4- Pico da Neblina, 5- Cabo Orange, 6- Jaú, 7- Serra do Divisor, 8- Monte Roraima;

[2] <u>Biological Reserves</u>: 9- Rio Trombetas, 10- Jarú, 11- Lago Piratuba, 12- Abufarí, 13- Guaporé, 14- Gurupí, 15- Tapirapé, 16- Uatumã;

[3] <u>Ecological Stations</u>: 17- Anavilhanas, 18- Iquê, 19- Maracá, 20- Rio Acre, 21- Maracá-Jipioca, 22- Caracaraí, 23- Jarí, 24- Juamí-Japurá, 25- Niquiá, 26- Coco-Javaes, 27- Cuniã, 28- Sauim–Castanheiras, 29- Jutaí-Solimões, 30- Mamirauá (State Ecological Station).

next examine the accessibility of lowland Amazonian reserves in relation to transportation routes available to potential intruders.

Accessibility of Existing Brazilian Nature Reserves

Taking advantage of high-quality RADAM maps available only for Brazil, and employing the 10 km criterion described above, we found that a mean of 75±19 percent of the areas of existing nature reserves in Brazilian Amazonia are accessible to intruders entering by foot from included or adjacent rivers and roads. This parameter fell between 40% in the least accessible to 100% in the most accessible reserves (N=29, Fig. 4.) All existing reserves, including those relatively far from settlements, are therefore accessible to entirely accessible. Reserve size explains 98% of the variation in accessible area ($r=0.99$, $N=29$, $p<0.01$).

There is little decrease in relative accessibility with reserve size. Larger reserves, given their present design, encompass greater numbers of rivers, permitting access to commensurately greater areas. However, the absolute amount of inaccessible "core habitat", beyond the practical limits imposed by physical distance, clearly increases with reserve size. We view large core areas as indispensable to safeguarding populations of important biotic elements, such as top predators and preferred game and timber species.

Controlling river or road traffic entering and leaving a reserve would in principle require a guardpost with similar levels of staff and infrastructure for each access point. The cost of protection thereby increases linearly with the number of entrance and exit points. To examine this further, we determined the number of access routes in nature reserves of Brazilian Amazonia and conservation areas proposed by the Manaus Workshop for the entire region.

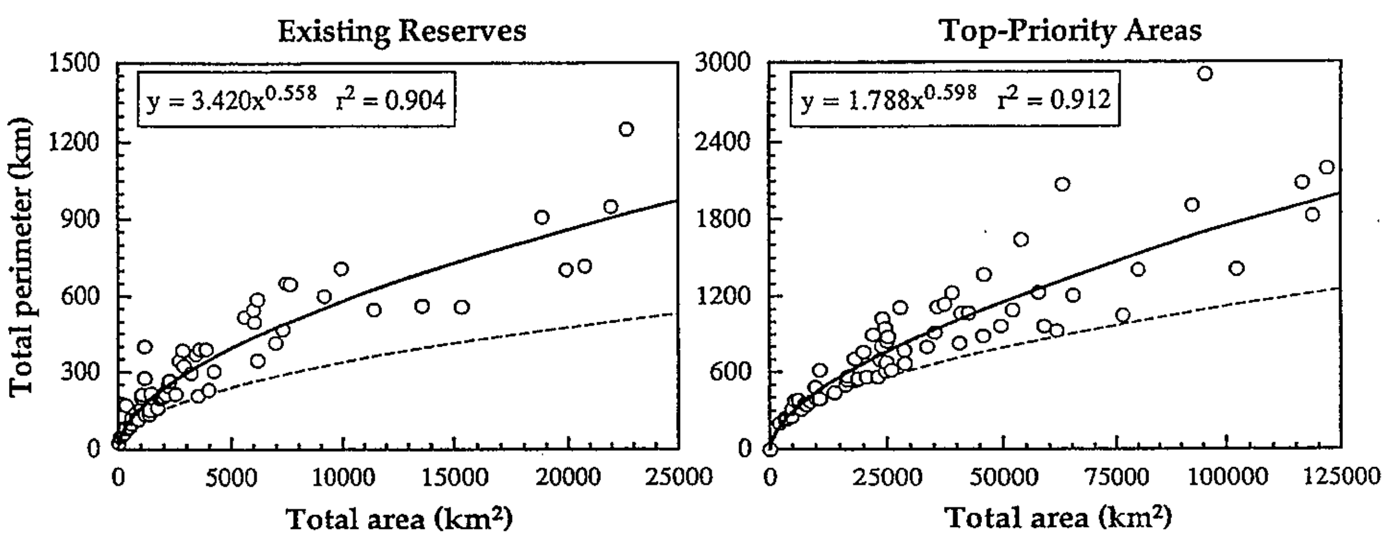

Figure 3. The relationship between total area and total perimeter of existing nature reserves (left) and proposed high-priority conservation areas (right) in Amazonia. Dashed lines represent the theoretical curve showing the lowest possible increment in perimeter length, as expected if reserves and priority areas were shaped as perfect circles. Top-priority conservation areas are based on those proposed by the Manaus Workshop (Conservation International 1990), but only a combination of the two highest priority levels are considered here.

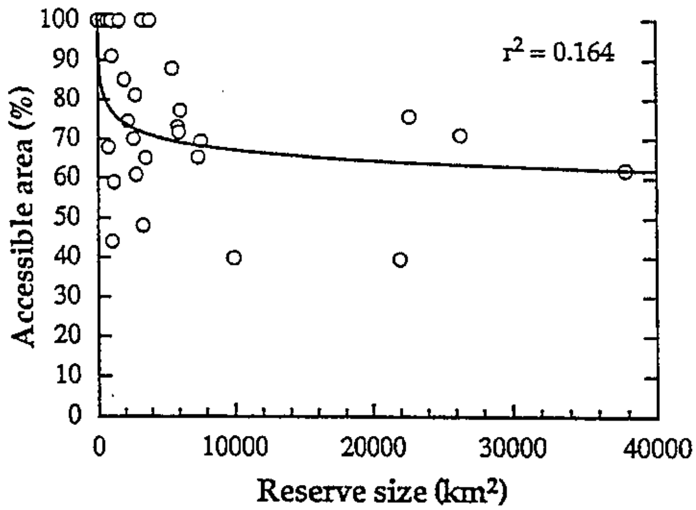

Figure 4. The relationship between the size of 29 Brazilian Amazonian reserves and the proportion of the total reserve area which can be accessible on foot, assuming a 10-km radius from the nearest point along navigable rivers and/or functional roads.

The number of rivers and roads providing potential access to conservation areas increases with their size and perimeter. This is true for both existing nature reserves (area: $r=0.73$, $N=30$, $p<0.001$; perimeter: $r=0.77$, $N=30$, $p<0.001$) and proposed priority conservation areas (area: $r=0.42$, $n=69$, $p=0.0003$; perimeter: $r=0.37$, $N=69$, $p=0.002$). These results confirm that even the largest lowland Amazonian reserves and designated priority areas, given their present configurations, are highly vulnerable to incursion. Size alone is an ineffective defense, because commensurately greater resources are not allocated to protect larger reserves. In Brazilian Amazonia, for instance, there is no relationship between the size of nature reserves and the number of guards ($r=0.27$, $p=0.14$, $N=30$) or total personnel employed ($r=0.05$, $p=0.79$, $N=30$). We therefore propose that new Amazonian reserves should, as much as possible, be delimited so as to gain the benefit of passive protection.

The Upper Watershed Reserve Model

Passive protection can be maximized by drawing boundaries along watershed divides, wherever practical. Watershed divides represent the least accessible points in the landscape, and therefore, as boundaries, benefit from passive protection to the greatest possible degree. By locating boundaries along topographic divides, a secondary conservation benefit derives from the protection of intact watersheds, with all their aquatic resources. A complete watershed in a roadless landscape, no matter how large, can be controlled at a single point: that at which the contained stream exits the zone of protection (Fig. 5). By concentrating personnel at that point, effective protection of the entire watershed can be achieved at minimum expense.

However, most existing Amazonian nature reserves are either bisected and/or bordered by navigable rivers in the legal public domain. From a defensibility standpoint, such reserves suffer from multiple disadvantages: (i) every river that traverses a reserve calls for at least two guardposts (Fig. 5a), (ii) inhabitants of legal settlements on a bank opposite a reserve boundary enjoy direct access to the reserve (Fig. 5b), and (iii) even frequent fluvial patrols by guards would be ineffective in averting illegal (and invisible) activities farther inland (Fig. 5a–b).

An upper watershed approach to reserve design in Amazonia would simultaneously (i) protect distinct biological assemblages in successive interfluvia, and (ii) address the issue of species complementarity within reserve networks (Pressey et al. 1993). Additional advantages of siting Amazonian reserves in headwater regions come in maintaining the spawning grounds of many migratory fish species (Ribeiro 1983;

Goulding et al. 1988) and in preserving a supply of potable water for downstream residents. Headwater regions often contain more topographic diversity than downstream areas, and thus may include a greater variety of aquatic and terrestrial habitats. The watershed approach would protect riparian corridors and their hydrologic regimes, the latter being critical to maintaining the complex dynamics of landform mosaics, plant succession, and the associated biodiversity (Salo et al. 1986; Kalliola et al. 1992; Puhakka et al. 1993; Naiman et al. 1993).

Biodiversity Gradients along Watersheds

If future Amazonian reserves are to be situated in headwater regions, it becomes important to consider how biodiversity is distributed longitudinally along the length of river basins in both the aquatic and terrestrial realms. In the aquatic realm, zonation of riverine fish faunas is strongly differentiated with respect to stream order (Horwitz 1978; Goulding et al. 1988; Ibarra & Stewart 1989), as is the hydrological regime. Frequency of flooding and sediment concentration increase upstream, while amplitude and duration of flooding increase downstream. The richness of Amazonian fish communities increases downstream (Ibarra & Stewart 1989), an observation that is supported by a clear correlation between water discharge and species diversity (Garutti 1983). In particular, a number of large-bodied aquatic vertebrates, including the Amazonian lung-fish or *pirarucú* (*Arapaima gigas*), giant river turtle (*Podocnemis expansa*) and pink dolphin (*Inia geoffroensis*) rely heavily on whitewater flooded forests (*várzea*), and are often missing in headwater regions. Moreover, many fish species of downstream pelagic habitats make lateral migrations into *várzea* and *igapó* (Ribeiro 1983; Cox-Fernandes & de Merona 1988; Goulding et al. 1988). These are also expected to be missing in headwater regions.

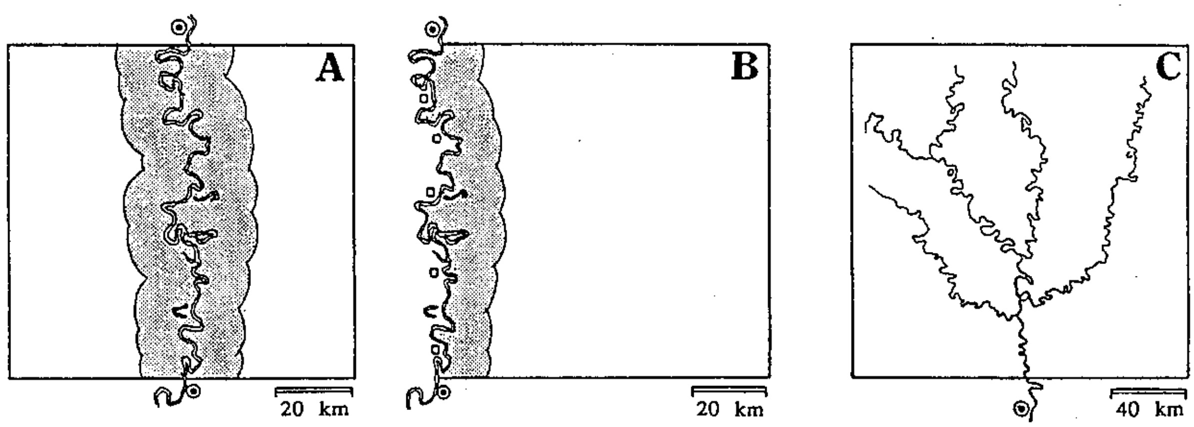

Figure 5. Hypothetical case scenarios in which Amazonian nature reserves are bisected (A) or bordered by a navigable river (B); or, alternatively, incorporate an entire upper watershed (C). Shaded areas, which are considered susceptible to uncontrolled access by illegal harvesters of forest products, represent sections of reserves bounded by arcs with a 10-km radius from the nearest point along rivers. Dotted circles indicate boat inspection outposts located upriver and downriver from reserve boundaries. Small open squares (B) indicate households within extractive communities legally settled on the opposite bank of established reserves.

On the other hand, recent fish collections in fast-flowing *terra firme* headwater streams in both the Guianan and Brazilian Shields appear to be extremely diverse, and have yielded numerous undescribed and possibly endemic species (L. Rapp–Py Daniel, pers. comm.). The occurrence of unique elements in the aquatic faunas of both upstream and downstream sections of Amazonian rivers thus argues for the creation of reserves in both regions.

The ecological and evolutionary influence of rivers on Amazonian terrestrial biotas generally increases with distance from the headwaters, as rivers broaden to become more effective barriers to terrestrial organisms (Wallace 1849; Ayres & Cutton-Brock 1991; Capparella 1992; Haffer 1992; Peres et al. in review). Greater duration and intensity of floods, lateral river channel migration, and floodplain succession in lower river basins, generally result in greater between-habitat (b), but not necessarily within-habitat (alpha) biological diversity along downstream sections of rivers. Headwater floodplains are more briefly and lightly flooded, and accordingly, their associated forests are more similar to those of the adjacent upland (Puhakka et al. 1993).

Topographic gradients across Amazonia are extremely weak, as illustrated by the fact that ocean-going vessels routinely navigate more than 3,000 km upstream. Consequently, the upper watersheds of major lowland Amazonian rivers contain most, if not all, of the terrestrial vertebrate alpha-diversity found in their central-lower catchment areas, a pattern that has been explicitly documented along the Rio Juruá for birds, primates, small non-volant mammals, and frogs (Peres, Malcolm, Patton, da Silva & Gascon, unpubl. data).

Flooded forest and river island species, however, may be excluded from, or represented in low densities, in headwater regions (Remsen & Parker 1983; Rosenberg 1990). The floras of downstream flooded (*várzea* and *igapó*) and unflooded forests are strongly differentiated (Prance 1979), and many plant species typical of downstream flooded forests may therefore be poorly represented in headwater sites. Junk (1989) estimates that roughly one fifth of the 4,000–5,000 Amazonian tree species are tolerant to periodical flooding of several weeks to many months, even though flooded forests account for only 4% of the region. A second set of reserves complementing those in headwater regions should thus be set aside to capture downstream biotas.

Conservation of Downstream Biotas

Clearly, the size, location, and design of nature reserves along Amazonian watersheds will explicitly have to take into account the countercurrent longitudinal biodiversity gradients in the terrestrial and aquatic realms. Downstream reserves should be designed partly for the purpose of conserving aquatic resources, with particular attention to the watercourse itself and its fringing *várzea* or *igapó* forests. Here, the approach of controlling whole watersheds at strategic entry points is inapplicable and other approaches will have to be developed. Greater investment in guards and other personnel for downstream reserves can readily be justified by the vital economic importance of aquatic resources to the human population of Amazonia (Smith 1979; Petrere 1982).

Longitudinal Coverage of Watersheds by Existing Nature Reserves

At present only three Amazonian national parks (Manu in Peru, Jaú in Brazil, and Canaima in Venezuela) encompass all or a substantial proportion of a major watershed. Other nature reserves tend to sprawl over two to several watersheds, and to include only a minor fraction of any one. In Brazil, for instance, only one Amazonian nature reserve covers an area equivalent to at least one quartile of the length of its main watershed axis (Fig. 6).

From a fluvial perspective, the nature reserves of Brazilian Amazonia are more or less evenly distributed between headwater regions and the confluence of major tributaries with the Amazon River (Fig. 6). However, the distribution of protected areas is very uneven across watersheds. Some major watersheds benefit from multiple reserves, while many others contain none. The existing array of nature reserves in Amazonia thus embodies weaknesses at two levels. First, there needs to be a better dispersion of protected areas across drainages, and second, both upstream and downstream conservation areas should be designed to maximize passive defensibility and cost effectiveness of enforcement personnel.

Proposed Priority Conservation Areas

The map prepared by the 1990 Manaus Workshop ("Biological priorities for conservation in Amazonia") features several dozen "high priority" areas for conservation action in Amazonia. These priority areas were intended to represent centers of endemism and diversity, but the evidence on which the areas were designated was often highly subjective, being based on the personal experiences of participants. Available evidence on endemism and species density gradients in Amazonia is greatly weakened by heterogeneity of sampling effort, clustering of collecting sites, and large geographical gaps between sampling localities, any or all of which may account for apparent range discontinuities (Gentry 1986, 1989; Nelson et al. 1990; Oren & Albuquerque 1991). Large gaps between some high-priority conservation areas tend to correspond to subregions which have received little or no sampling (Juruá river: Peres, Malcolm, da Silva, Patton & Gascon, unpubl. data). Consequently, the Manaus Workshop map should not be taken uncritically as a statement of reality. Instead, it should be recognized as a good faith effort to locate biologically important regions within Amazonia, with the understanding that the information upon which it is based will be subject to continuing revision.

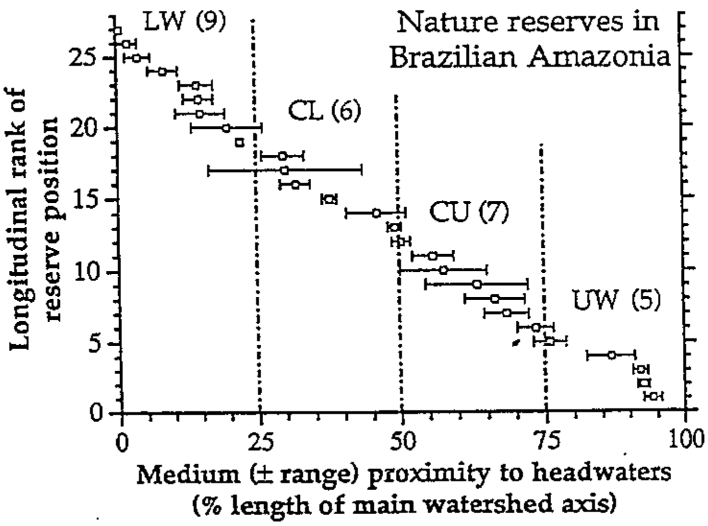

Figure 6. Relative distribution of nature reserves ranked longitudinally in relation to watersheds of primary Amazon River tributaries of Brazilian Amazonia. Numbers (in parentheses) indicate the regional occurrence of lower- (LW), central-lower (CL), central-upper (CU), and upper watershed nature reserves (UW).

To the degree that the Manaus Workshop map does accurately portray biologically distinctive areas within Amazonia, it should be noted that the locations of many of them, as well as those in previously published maps for individual forest-dwelling taxa, lie in the upstream portions of river basins (Prance 1982; Brown 1987). We therefore suggest that headwater reserves, if appropriately located and delimited, can satisfy both biological and defensibility criteria.

Costs of Implementing Reserves

Espirito Santo & Faleiros (1992) recently estimated the total cost of implementing the existing 99 National Parks, State and Federal Biological Reserves, Ecological Stations (or Reserves), National Forests, Extractive Reserves, and Environmental Protection Areas in the Legal Brazilian Amazon (a politically defined region of 5 million km^2), at US $524 million. Included were the costs of land purchase, demarcation, management plans, infrastructure, and equipment. Maintenance costs, including staff salaries, are estimated at US $29.5 million for the first year, and US $27.1 million for subsequent years.

By far the largest component of the estimated cost (82%) was that for land acquisition. The complex land tenure system in Brazil is such that most Amazonian nature reserves are not entirely owned by the national or state governments: only 13 of 32 federal nature reserves in this region are wholly in the public domain (Espírito Santo & Faleiros 1992). Overall, private landholdings and claims amounted to 65% of the Legal Brazilian Amazon in 1990 (INCRA 1990). States under strong development pressure are already at least 83% in private hands (Maranhão and Acre), if not entirely so (Mato Grosso and Tocantins). Clearly, the matter of land property rights looms as a major impediment to implementing the currently designated conservation system in Amazonia. Proposals to add to the existing system will have to take into account the rapidly rising cost of repatriating land from private ownership. The infinite green horizon seen by anyone who flies over the Amazon seems reassuring, but it is an illusion. The hard reality is that much of the land is already under claim.

RECOMMENDATIONS

Our watershed reserve model calls for a two-tiered structure of Amazonian reserves targeted to both the upstream and the downstream sections of major watersheds. A system of large (greater than 1 million ha), inviolate nature reserves encompassing the upper sections of intact drainage basins would (i) permit maximum control over boat traffic at minimal cost in personnel and infrastructure, and (ii) be intrinsically more resistant to human incursion than nearly all existing reserves. Preference in locating new nature reserves should be given to drainages currently lacking them. On the south bank of the Amazon within Brazil, unprotected basins include the upper sections of the Jutaí (Amazonas), the Teles Pires (Pará/Mato Grosso) and the Irirí rivers (Pará), and some tributaries of the Juruá and Purús (Acre). Networks of geographically clustered nature reserves could be interconnected by corridors running along headwater divides (Harris 1985). A similar linkage approach has recently been proposed for Venezuelan parks (Yerena & Romero 1992).

An additional system of central-lower watershed nature reserves should be established to complement those in headwater regions. Downstream reserves will be essential to safeguarding representative *várzea* and *igapó* habitats, as well as important commercial fisheries. Such "flooded-forest" reserves will assure the continued functioning of intact habitat mosaics with their high productivity and distinct biodiversity (Prance 1979; Junk 1989), and will preserve the lateral migration of downstream aquatic organisms as well as the seasonal movements of forest wildlife using both flooded and unflooded forests (e.g. Peres 1993). Almost inevitably, downstream reserves will have to be sited in areas of relatively high human densities, and therefore cannot be expected to protect nature in pristine form. Effective implementation of such reserves may therefore require greater local-community participation, a process currently being tested by the *Projeto Mamirauá* in the lower Japurá river (Polshek 1993; J.M. Ayres, pers. comm.).

Control posts should be sited downriver of both headwater and flooded-forest reserves, either on the river bank or on floating docks in deep water at which boats could conveniently stop. Wherever practical, posts should be located within ready access of small towns, because it is difficult to recruit and retain competent personnel for duty in remote locations.

A new institutional approach to training and support of reserve personnel must be adopted if reserves are to be effectively defended in the future. Park guards in Amazonia are commonly recruited locally from the lowest social stratum. Accordingly, guards tend to be uneducated, poorly paid, and ill equipped. Such individuals are easily intimidated and hesitate to assert themselves to curtail unlawful activity. Effective enforcement of conservation policy is entirely dependent on the authority and respect given to guards. Therefore, it is imperative that guards be better trained and supplied with standard uniforms, weapons and ammunition, and empowered to confiscate illegal materials and to arrest violators.

Additional nature reserves are needed to increase the representation of fully protected areas in Amazonia, and to fill some of the many large gaps between existing reserves. The existing system of nature reserves should be overhauled to the extent that large reserves can be redrawn, interconnected, and consolidated into comprehensive reserve networks. Small reserves should be retained unless the cost of maintaining them withdraws resources from more important reserves elsewhere.

Finally, we suggest that strict nature reserves should not be compromised by economic activities other than ecotourism if full complements of flora and fauna are to remain intact (Robinson 1993). A complementary network of production and indigenous reserves will assist in minimizing habitat fragmentation and maintaining biodiversity within the Amazonian landscape, but they should be designed to buffer and supplement, rather than to replace, an inviolate system of strictly protected nature reserves.

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