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Supplementary Materials for

Empty forest or empty rivers? A century of commercial hunting in Amazonia

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text S1. Historical documents list. Numbers are consistent with the primary historical documents described in the Materials and Methods section.

(1) *Amazonas State official commercial records*

Amazonas (State). *Relatorio apresentado ao Exm. Sr. Dr. Felippe de Santiago Minhos, Inspetor do Thesouro, por Domingos José de Andrade, Escrivão, servindo de Administrador da Recebedoria, em maio de 1904* (Manaus, 1906).

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text S2. Comparing the impacts of contemporary subsistence hunting versus historical commercial hunting in Amazonia

Subsistence hunters are mostly central-place foragers (*9, 17, 20-22, 47*). Even at the peak of commercial hunting, most ungulate hides traded were extracted and tanned from animals hunted primarily for their meat by subsistence hunters. Regions containing high concentrations of rubber trees (*Hevea brasilensis*), such as the upper Purus, Juruá and Madeira rivers, were intensively colonized from the 1870s onwards, through the system of rubber landholdings known as *seringais* (*23-26*). Each *seringal* had a central warehouse (*barracão central*) at the bank of the main river, which received goods from the major towns (Manaus and Belém) and returned forest products through boats and ships (*23-27*). A few pathways spread out from the central warehouse, where dozens to hundreds of huts were situated, each occupied by a rubber tapper and his family. Some important older traders from the Sena Madureira Municipality in Acre (see Figs. 3 and 5) reported that one of the largest *seringais* of the upper Purus, the Guanabara Seringal along the Iaco River, had about 400 rubber tapper huts (*colocações*) [Raimundo Diniz, Waldo Diniz and Antonio Diniz pers. com.]. Each rubber tapper (*seringueiro*) walked daily one of three or more trail loops from his hut that comprised a route of 10-20 km each day. Some huts were as far as 40 km from the main river, creating a diffuse pattern of forest hunting effort in these places. In regions where the density of *Hevea brasiliensis* was low, the spatial pattern and intensity of hunting effort were more diluted than in the regions densely occupied through *seringals.* In the *varzea* floodplains, the spatial pattern of commercial hunting was different again, with access mostly from canoes, targeting the black caiman and the manatee in particular. Such variations in hunter behavior make it difficult to generalize hunting effort at large spatial scales.

During the peak years of the Amazonian fur trade, there were some professional commercial hunters who undertook long hunting journeys, accumulating hides for up to six months a year. To this day, elderly hunters from the hinterlands remember when an entire herd of white-lipped peccaries was slaughtered, or caimans were hunted out along entire river basins, leaving “tons of meat behind for vultures and piranhas”. Commercial hunters were especially motivated by the high prices of feline pelts, to which they allocated major harvesting effort, often using artisanal traps baited with other hunted animals, such as monkeys, sloths, caimans, river dolphins, agoutis, or tinamous.

The weight of skins compared to that of meat is also a determining factor in what was probably a larger spatial effort and higher intensity of 20th-century commercial hide harvesting compared with present-day subsistence hunting. For instance, while a white-lipped peccary skin weighs only about

1.1 kg, the full adult carcass can weigh 45 kg. Thus a subsistence hunter could only carry at most two animals, while a commercial hide hunter could carry skins of at least 50 animals with a comparable effort.

Carnivores are ignored by present-day subsistence hunters, but in the past they were intensely hunted due to high pelt prices. Pelts of margays, ocelots, jaguars, and giant otters were sometimes traded for a new rifle with a box of shotgun cartridges, or a similar amount in cash. Such details are reported by elderly Amazonian forest dwellers, who are often nostalgic about the historical fur trade. Economic incentives for the carnivore fur trade no longer persist in Amazonia, although carnivores are sometimes killed to protect humans and livestock.

The only available knowledge of contemporary subsistence harvests comes from a study of the whole Brazilian Amazon region in 1996 (*8*), which estimated that between 6.4 and 15.8 million mammals were harvested each year among some 8 million rural people. Indigenous people and their subsistence takes are predominantly not included in these totals. In order to compare wildlife harvests for contemporary subsistence purposes with those for the 20th century hide trade, we used the ratio between the total number of animals hunted and the number of inhabitants in rural areas (hunted animals per rural inhabitant). Thus, of the 8,158,897 rural people inhabiting the entire Brazilian Amazon in the 1990s, 1,446,576 lived in the central-western Brazilian Amazon (states of Acre, Amazonas, Roraima and Rondônia) (*145*). Using estimates of total annual 1990s harvest in the entire Brazilian Amazon of 611,527–1,499,318 white-lipped peccaries, 551,949–1,353,248 collared peccaries, and 278,704–683,317 deer (mostly *Mazama americana*) (*8*), implies that some 108,424–265,830 white-lipped peccaries, 97,861–239,932 collared peccaries, and 49,414–121,152 deer were hunted annually for subsistence in the central-western Brazilian Amazon during the 1990s by non-indigenous rural people. These values are fairly consistent with our estimates of the annual 20th-century harvest for the hide and skin trade within the same region, despite the smaller human population.

Based on our hide production estimates, the annual harvest per capita of rural human population was at least 3.8 (white-lipped peccary), 3.7 (collared peccary) and 2.2 (red-brocket deer) times higher in the late 1930s than for non-indigenous subsistence takes in the 1990s. In 1969, the equivalent figures were respectively 0.6, 2.7 and 1.3 times higher than the 1990s. Lower estimates per rural inhabitant for the white-lipped peccary in the late 1960s reflects its likely population declines in accessible areas induced by commercial hunting, when the offtake was 33% of that in the 1930s, and about 30% of the collared peccary harvests in the late 1960s, despite both species having experienced similar harvests in the 1930s. However, both peccary species had similar offtakes in the 1990s (*8*), suggesting that the white-lipped peccary has experienced some degree of population recovery since the end of the Amazonian hide trade, despite the continued pressure of subsistence hunting. This combined evidence suggests that the economic incentives of 20th-century commercial hunting led to a more intensive harvest (both in total and per rural inhabitant) than contemporary subsistence hunting.

Currently, there are two very different scenarios concerning subsistence hunting (or illegal commercial hunting for wildlife meat) in Amazonia. Since the 1970s, changes in land use have been taking place especially along the southern and eastern Amazon, the so-called Arc-of-Deforestation, driven by expanding large-scale agricultural and cattle ranch frontiers (*5*). Deforestation has wiped out vast areas of potential refuges, and the opening of highways and their inherent secondary roads has further increased access to these erstwhile source areas. On the other hand, in regions where access is restricted to waterways, the traditional occupancy pattern remains and central-place hunting behavior ensures limited access to remaining refuges. In addition, with the final collapse of the Amazonian rubber trade in the 1980s, the spatial extent of hunting effort has further diminished in *seringal* areas that were previously densely populated, and settlements have become more concentrated along the margins of major rivers (*148*).

text S3. International demand for Amazonian hides through time

With the Japanese attacks on British, French and Dutch colonies in Southeast Asia at the onset of World War II (WWII), the supply of rubber (*Hevea brasiliensis*, Bignoniaceae) to the world was suddenly interrupted (*23-25*). In an attempt to overcome this bottleneck, the United States signed the Washington Agreement (1942) with Brazil, in order to gain access to rubber production areas in the Amazon (*23-25*). The US government invested huge amounts of capital in the Amazon to restructure natural rubber stands (*seringais*), finance the influx of extractive labor for the region, and re-equip and upgrade a commercial fleet of cargo boats to take advantage of fluvial navigation. In return, all rubber surpluses produced by Brazil had to be exported exclusively to the United States (*23-25*). Between 35,000 and 80,000 'rubber soldiers' were sent mainly from northeastern Brazil to repopulate the *seringais* (*23-25*), effectively contributing to the increase in hunting effort, both in terms of spatial scale and intensity.

The Brazilian Government then created the Rubber Credit Bank (BASA), which monopolized the financing of the *seringais* and the rubber trade operations (*23-25*). Previously, such control was exercised by warehouses and exporter hubs in Manaus and Belém. Breaking down these traditional trade relationships and the inherent system of debt peonage was not an easy task (*24*). Thus the established trading companies and warehouses often interfered in the Washington Agreement goals to their own commercial advantage; however they also lost exclusive rights to the rubber trade, leading to the bankruptcy of some traditional warehouses (*24,139*). For example, the merchant empire of the J. G. Araujo Company began to decline in this period (*139*), although it persisted until the 1990s.

Many other Amazonian extractive products were not included in the Washington Agreement, in order to concentrate regional labor solely on the extraction and production of rubber latex (*27,108-110*). Consequently, during WWII, exports of other significant extractive products such as Brazil nut (*Bertholletia excelsa*, Lecythidaceae) and Brazilian Rosewood oil (*Aniba roseodora*, Lauraceae) were discontinued (*27,140-142*) (fig. S1). Thus, an interruption of the consumption of Amazonian hides and skins would be expected not only in Europe (where an active ground war was ensuing) but also in the US, where the economy was presumably on a war footing due to its war efforts. Yet, surprisingly, the Commercial Association of Amazonas State (ACA) reported (*141*):

> *"(...) this [hides and skins trade] was one of the sectors least sacrificed with the policy restrictions of regional products by US markets under the guise of mobilizing labor for rubber production (…). The market for this product, for which demand has never*

suffered interruptions, remained perfectly stable, justifying the constant flow of buying and selling in the local market and export transactions for Yankee markets."

The post-war era started a new phase in the Amazon, which began amid strong economic difficulties (*139*). With the end of international investments and consequently the weakening of BASA, as well as the widespread bankruptcy of the traditional Amazonian warehouses and exporters (*139*), the transport of goods was seriously affected. The size of commercial fleets operating along Amazonian rivers decreased, as did likewise the flow of extractive products. It is not possible to determine the exact scale of declining hunting effort due to losses in extractive labor leaving the forest interior. However, local time series do not show generally decreasing trends in the number of skins traded in the post-war period (Fig. 3). In addition, the number of hide traders in Manaus increased after WWII, including high-tech tanneries processing caiman leather (*27*,*143*).

The decline of indexed prices of hides (mostly deer and peccaries) should not necessarily be understood as a decline in demand or hunting effort, especially in a period of high inflation in Brazil (*144*). Moreover, the rural population throughout the Amazon grew until the 2000s according to the decennial population census conducted by the Brazilian Institute for Geography and Statistics (IBGE) (*145*) (fig. S2).

From the middle of WWII, *jute* fiber (*Corchorus capsularis*) emerged as one of the most important extractive products of the state of Amazonas (*146*) (fig. S1). This species was cultivated in floodplains, so colonization of this habitat increased considerably after WWII, as *jute* plantations expanded especially during the 1950s (*147*). It is likely that this spatial increase in hunting effort was responsible for the distinctive trends in black caiman and capybara harvests, which remained relatively steady until the 1950s (Fig. 2).

Increasing prices of hides and pelts in the 1960s spurred further hunting effort, but with a population 68% larger than in 1940 (*145*) (fig. S2). In the 1970s, the Amazonian fur trade remained intense despite being officially banned (*32-36*). Loopholes allowed exports of stockpiled hides, but commercial hunting was no longer legal (*33-36*). However, hide landings at the port of Manaus increased after the Brazilian Faunal Protection Law was passed (Fig. 1), attesting to the ineffective enforcement of the law in Amazonia. The paving of both the Transamazon and Belém-Brasilia highways and associated colonization policies contributed to large-scale deforestation in the Amazon (*5*), with a concomitant increase in hunting effort in previously intact areas (*38*,*39*). However, official statistics on the hide trade were discontinued in the early 1970s.

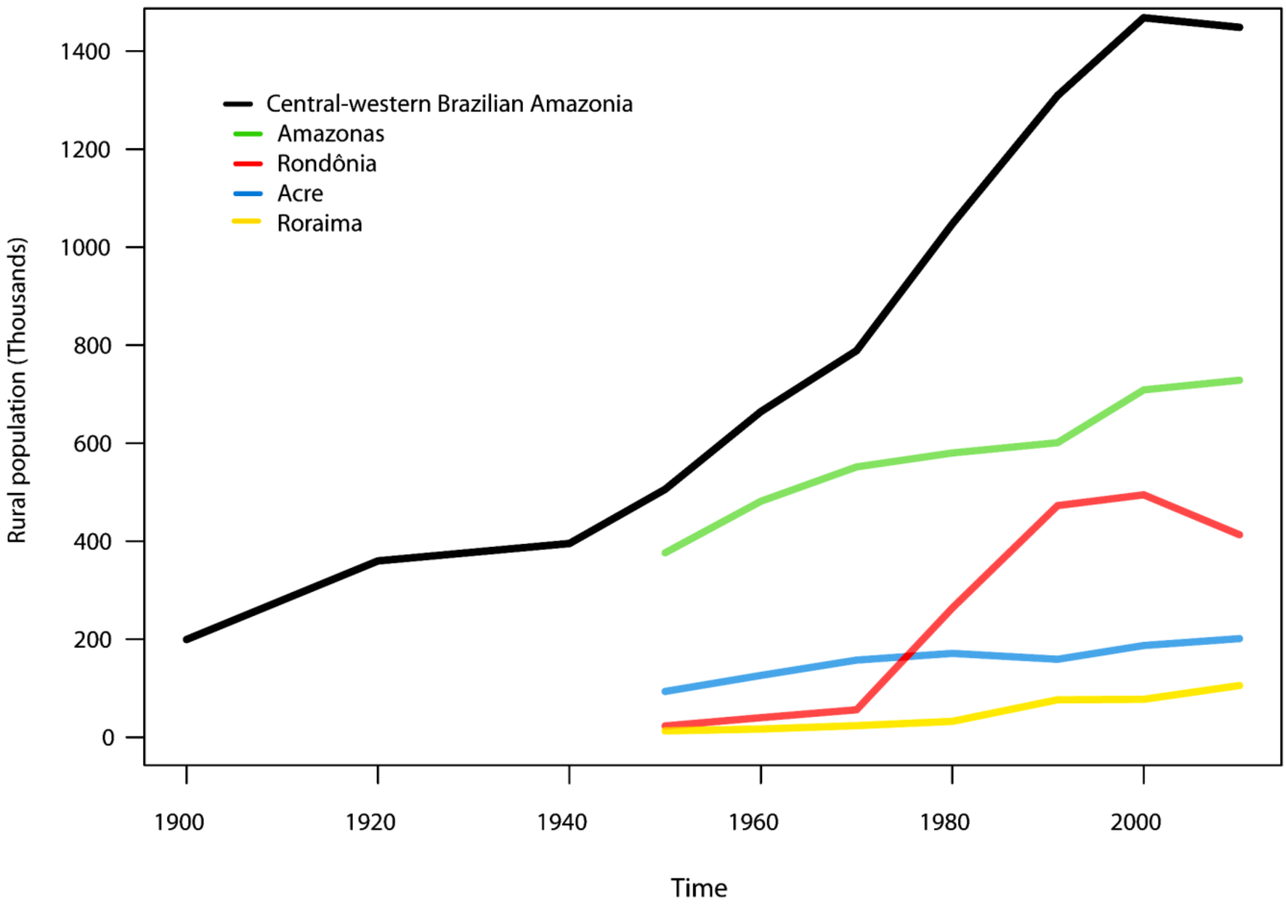

fig. S1. Rural population in the central-western Brazilian Amazon. Data are obtained from decennial censuses performed by the Brazilian Institute for Geography and Statistics (IBGE) http://seculoxx.ibge.gov.br (*145*). The black line represents the sum of the four colored lines.

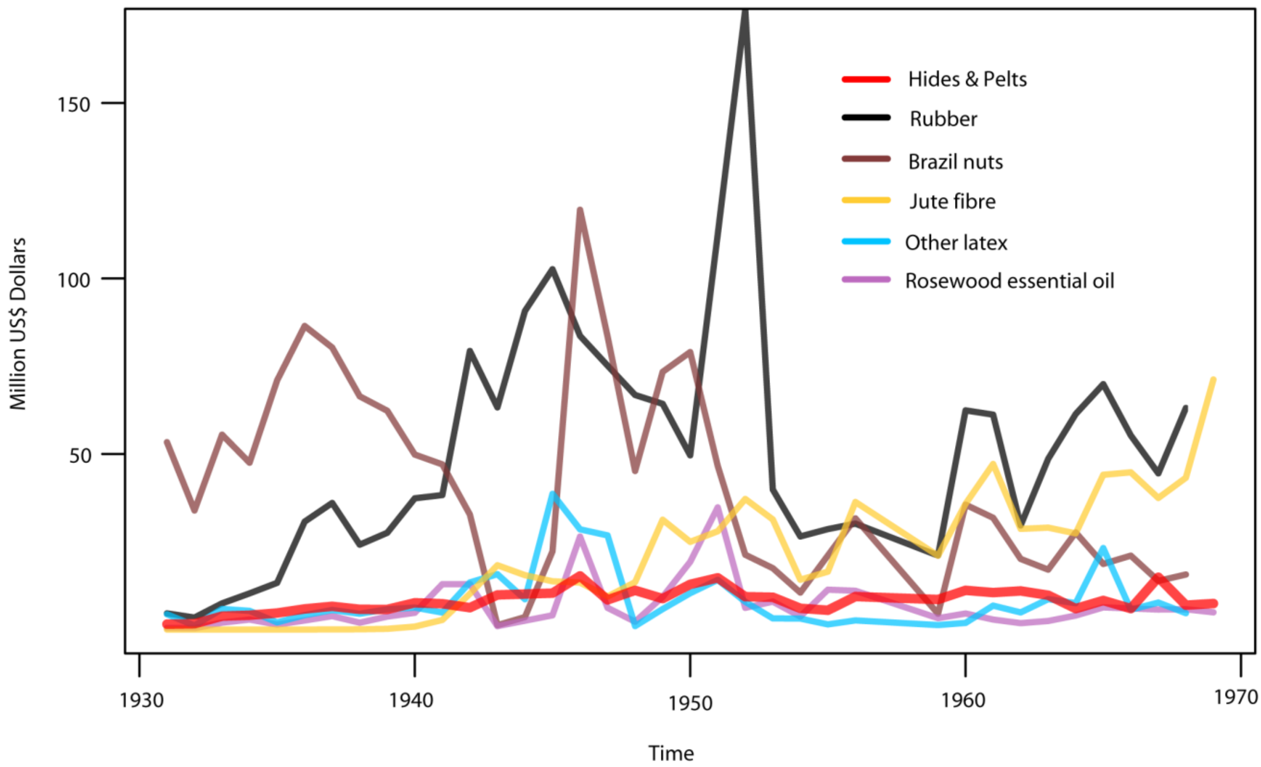

fig. S2. Central-western Brazilian Amazon yields (U.S. dollars in 2015 currency equivalence) for foremost 20th century products. Yields for the years 1945-1950, 1953-1956 and 1959 are restricted to Amazonas State. ‘Other latex’ products include *Balata* (genera *Manilkara*, *Chrysophyllum*, *Ecclinusa*, *Pouteria*, *Micropholis* of Sapotaceae) and *Sorva* (*Couma*, Apocynaceae). Note the sharp downturns for Brazil nut and rosewood essential oil in 1943-1944, contrasting with the rise in hides and pelts during WWII. Note also the steady increase in yields of jute fibre (*Corchorus capsularis*, Malvaceae) after the onset of WWII.

table S1. **Average hide weights of commercially-hunted species**.

Species	Average weight (Kg)	Total number of hides weighed	Total weight (Kg)	Modeled harvests (Kg) 1904-1969	Animals harvested 1904-1969
Manatee	20.34	41	834	2,298,491	113,033
Capybara	3.27	393	1,287	3,402,542	1,040,533
Ocelot / Margay	0.44	3,584	1,594	353,795	804,080
Jaguar	1.51	537	812	275,671	182,564
Neotropical otter	0.59	609	362	213,778	362,335
Giant otter	1.10	787	868	425,141	386,491
Collared peccary	0.77	103,532	79,500	4,191,722	5,443,795
White-lipped peccary	1.10	65,847	72,754	3,421,828	3,110,753
Red brocket deer	1.49	77,374	114,922	6,186,806	4,152,218
Black caiman	2.55	12,786	32,600	11,259,447	4,415,469
Common agouti	0.35	92	32	32,229	92,082
Amazonian brocket deer	0.53	153	81	46,743	88,194
Tapir	13.41	22	295	329,479	24,570
Iguana	0.07	227	17	180,717	2,581,667
Tegu lizard	0.15	160	24	18,797	125,314
Caiman lizard	0.13	16	2	7,156	55,047
Boa / Anaconda	3.19	62	198	154,842	48,540
Spectacled caiman	2.26	18,823	42,467	635,911	281,376

These measures were obtained from historical documents, which specify the number of hides traded per species and their weight. We used this information to convert modeled harvests in kilograms for each species to numbers of individuals harvested by dividing the hide biomass by species-specific hide weights.

table S2. Intrinsic Rate of natural increase (R_{max}) for game species and parameters required for its calculation by the Cole equation (*114*)**.** See references in parentheses.

Species	R_{max}	Age of first reproduction	Age of last reproduction	Annual offspring per female
Manatee	0.1*	6 (*115*)	40 †	0.33 †
Jaguar	0.23 (*113*)	3.5 (*113*)	14 (*113*)	0.5 (*113*)
Giant otter	0.26*	2.5 (*116*)	10 (*116*)	0.575 (*116*)
Black caiman	0.29*	15 (*117*)	40 (*118*)	19.65 (*119*)
Neotropical otter	0.32*	2 (*120*) ‡	9.43 (*121*)	0.575 (*120,122*) ‡
Red brocket deer	0.35*	1.1 (*113*)	13.8 (*113*)	0.44 (*123*)
Ocelot and Margay	0.46 (*113*)	1.5 (*113*)	10 (*113*)	0.75 (*113*)
White-lipped peccary	0.46*	1.5 (*113*)	13.25 (*113*)	0.74 (*124*)
Collared peccary	0.70*	0.9 (*113*)	13 (*113*)	0.95 (*125*)
Capybara	0.84*	1.5 (*126*)	9 (*113*)	3 (*126*)

* This study.

† V. M. F. da Silva personal communication for captive manatees.

‡ Extrapolated from related species.

table S3. Area of terrestrial and aquatic habitats, and their accessibility by hunters, under two hunting catchment area scenarios (buffers of 5 and 10 km around all settlements) in the central-western Brazilian Amazon.

Habitat	Area - km^2 (%)
Terrestrial habitat	
High-water season	1,909,768 (88)
Low-water season	2,064,818 (95)
Hunting area – A_{hunt} (buffer 5 km)	131,619 (7)
Hunting area – A_{hunt} (buffer 10 km)	370,207 (19)
Refuge – A_{refuge} (buffer 5 km)	1,778,149 (93)
Refuge – A_{refuge} (buffer 10 km)	1,539,561 (81)
Aquatic habitat	
High-water season	265,976 (12)
Low-water season	110,927 (5)
Hunting area – A_{hunt} (buffer 5 km)	32,167 (29)
Hunting area – A_{hunt} (buffer 10 km)	60,899 (55)
Refuge – A_{refuge} (buffer 5 km)	78,760 (71)
Refuge – A_{refuge} (buffer 10 km)	50,028 (45)
Central-western Brazilian Amazon	2,175,744 (100)

Percentages are shown in brackets. Percentage areas for hunting area (A_{hunt}) and refuge (A_{refuge}) are maximal for the corresponding habitat category, being expressed as percentages of the high-water season area for terrestrial habitat, and of the low-water season area for aquatic habitat. See Materials and Methods for further details of spatial analyses.

table S4. Comparison between Robinson-Redford production index (*49*, *50*) and commercial harvests at two historical peaks for terrestrial species.

Species	λ	K (animals per km^2)	Production (animals per km^2)	Commercial harvest (animals per km^2)			
				1930s		1960s	
				Hunting area (km^2)			
				131,619	370,207	131,619	370,207
Collared peccary	2.01	8.05	0.980	1.85	0.66	2.76	0.98
White-lipped peccary	1.58	5.24	0.367	2.08	0.74	0.66	0.23
Red brocket deer	1.42	5.67	0.285	1.00	0.36	1.29	0.46
Jaguar	1.26	0.05	0.002	0.07	0.03	0.06	0.02
Ocelot / Margay	1.58	0.96	0.067	0.26	0.09	0.34	0.12

Maximum production was calculated for two hunting area scenarios using 5 km and 10 km buffers around settlements, yielding hunting areas of 131,619 km^2 and 370,207 km^2 respectively. Rate of finite growth, λ, is given by $e^{R_{max}}$; K is the carrying capacity; and maximum production is calculated as $0.6K(\lambda - 1)0.2$, where $0.6K$ is the density at which maximum population growth is assumed to occur and where $F = 0.2$ is a factor accounting for natural mortality (*49*, *50*). Green represents harvests that were lower than maximum production in the associated area, and red represents harvests that were unsustainable according to this production index. The sizes of catchment areas are taken from table S3. See Materials and Methods for details on maximum production calculations. For further details see previous publications (*49*, *50*).

table S5. Comparison of the minimum refuge area required for maximum sustainable harvests (A_{MSY}) according to the Joshi and Gadgil model ($\alpha = 1/\lambda$) to actual refuge area (A_{refuge}) in the central-western Brazilian Amazon.

Species	α	5 km buffer		10 km buffer	
		A_{MSY}	A_{refuge} / A_{MSY}	A_{MSY}	A_{refuge} / A_{MSY}
Terrestrial					
Collared peccary	0.50	129,833	13.70	365,185	4.22
White-Lipped peccary	0.63	225,346	7.89	633,836	2.43
Red-brocket deer	0.70	314,076	5.66	883,407	1.74
Ocelot / Margay	0.63	225,346	7.89	633,836	2.43
Jaguar	0.79	508,967	3.49	1,431,582	1.08
Aquatic and semiaquatic					
Capybara	0.31	24,436	3.22	46,263	1.08
Neotropical otter	0.73	85,293	0.92	161,481	0.31
Giant otter	0.77	108,330	0.73	205,095	0.24
Black caiman	0.75	95,612	0.82	181,016	0.28
Manatee	0.90	305,850	0.26	579,046	0.09

A_{MSY} is the size of refuge required to achieve a theoretical maximum sustainable yield in relation to A_{hunt} and is calculated through $A_{MSY} = \alpha A_{hunt}/(1-\alpha)$. A_{hunt} is calculated for two hunting area scenarios using buffers of 5 km and 10 km around historical settlements – see table S3. Area is presented in km^2. In cases where $A_{MSY} > A_{refuge}$, harvests are assumed to be sustainable, and vice-versa. Refuge sizes for terrestrial species varied from 1.08 to 13.70 times larger than the size of refuge required to achieve a theoretical maximum sustainable yield (A_{MSY}), while for aquatic and semiaquatic species they were from 0.09 to 3.22 times larger than A_{MSY}. See Materials and Methods for details of these calculations. For further details see Joshi and Gadgil (*51*).