Rainforest metropolis casts 1000 km defaunation shadow

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Tropical rainforest regions are urbanizing rapidly, yet the role of emerging metropolises in driving wildlife overharvesting in forests and inland waters is unknown. We present the first evidence of a large defaunation shadow around a rainforest metropolis. Using interviews with 392 rural fishers we show that fishing has severely depleted a large-bodied keystone fish species, tambaqui (*Colossoma macropomum*), with an impact extending over 1000 km from the rainforest city of Manaus (population 2.1 million). There was strong evidence of defaunation within this area, including a 50% reduction in body size and catch rate (catch-per-unit-effort). Our findings link these declines to city-based boats that provide rural fishers with reliable access to fish-buyers and ice, and likely impact rural fisher livelihoods and flooded forest biodiversity. This novel empirical evidence that urban markets can defaunate deep into rainforest wilderness has implications for other urbanizing socio-ecological systems.

ecological footprint | freshwater biodiversity | fishing down | overfishing | urbanization

Introduction

The tropics harbor two-thirds of the Earth's biodiversity (1), and are experiencing rapid human population increase, urbanization and economic transitions (Fig. S1). These demographic changes are resulting in higher food demand from tropical consumers, particularly for animal protein (2). Much of this demand is being met by the expansion of farmed meat production, which has resulted in widespread land-use change (3). However, wild meat such as fish and bushmeat is also an important food for hundreds of millions of tropical consumers, from the poorest and most vulnerable people (4, 5) to wealthier urban residents (6, 7). The consumption of wild meat is causing pan-tropical defaunation because exploited populations are widely harvested above the maximum sustainable yield (5, 8–10). The severe decline in abundance of exploited species can cascade onto ecosystem functioning and human well-being, causing food insecurity by reducing access to safe and affordable sources of protein and micronutrients (9, 10).

There is now evidence that urban demand is an important driver of tropical wildlife depletion. Marine defaunation shadows have been observed around urban markets, in the form of market proximity-dependent declines in target seafood species, or even whole fish communities (11–14). Tropical inland fisheries have also been over-exploited (8), yet evidence is based on local effects of rural-subsistence fishing (8, 15), so the impacts of overfishing inland waters to supply urban markets are unclear. Modelled bushmeat market data suggesting that rainforest defaunation shadows exist around urban areas (16–18) are supported by recent empirical evidence that *in situ* terrestrial wildlife population impacts are greatest nearer small towns (19). Although forest degradation has been observed spreading from a tropical forest metropolis to meet demand for wood (20), the role of emerging metropolises (>1 million people) in driving large-scale wildlife overharvesting in rainforests and/or inland waters is unknown.

Understanding metropolitan impacts on biodiversity and ecosystems is critical in the Amazon, the world's largest tropical rainforest and drainage basin with over 1 million km^2 of freshwater ecosystems (21) and more fish species than the Congo and Mekong basins combined (22). Human demographic changes in the Amazon illustrate how the demand for wild meat harvest has urbanized. Three quarters of the population of the Brazilian Amazon lived in rural areas in 1950, whereas three quarters - around 18 million people - now live in urban areas (23). Recent evidence shows that urban consumption of wild meat in Amazonia is commonplace (7), as is the case across the forested tropics (5) where urbanization continues (Fig. S2). This raises an important question about the defaunation shadows cast by rainforest cities, in particular large metropolises, in so-called tropical 'wilderness' areas of largely structurally intact rainforest and sparse human population (24).

For the first time, we examine how far the defaunation shadow of a metropolis extends into the forested 'wilderness'. We then assess which factors determine the extent of this shadow, and discuss the potential ecological and social consequences. Specifically, we use fisher surveys to investigate the impacts of feeding the Amazon's largest city, Manaus, by harvesting its consumer's favorite fish species, tambaqui (*Colossoma macropomum*). Through these surveys we measure the principal indicators of overharvesting for targeted fish species; the captured individual's body size and catch-per-unit-effort in biomass (CPUEb) (8). While ensuring to incorporate only fishing activity that occurred within close proximity to the interviewed fisher's community (see Methods for more details), we surveyed a 1267 km gradient of fluvial travel distance from Manaus. The gradient was located along the Purus River, which is Manaus' principal fishing ground. The Purus watershed has very low human population densities and high remaining forest cover (Fig. 1; Table S1), bringing our study area well within the definition of a tropical wilderness area (24). It is also one of just three major Amazonian

Significance

Tropical wilderness areas of largely pristine habitats and low human population densities are witnessing rapid urbanization. However, the urban impact on harvested wildlife populations is largely unknown. An extensive dataset on the population status of a keystone fish species was generated by interviewing hundreds of rural Amazonians about their lifetime fishing activity, along a heavily fished but otherwise relatively pristine river. Data reveal that the fish become much smaller and harder to catch when travelling towards a rainforest metropolis of over 2 million residents. This trend extends over 1000 km from the city. We show how urban connectivity drives this depletion, and discuss how wider forest diversity and human livelihoods may suffer as a result.

Reserved for Publication Footnotes

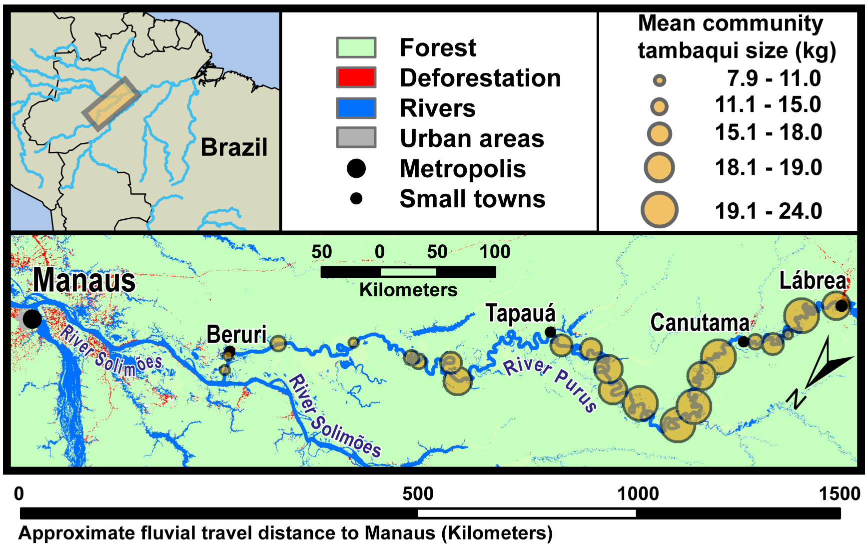

Fig. 1. Map of the Purus River. Mean community tambaqui size corresponds to the largest tambaqui caught in the fishers' lives, as presented in Fig. 2*A*.

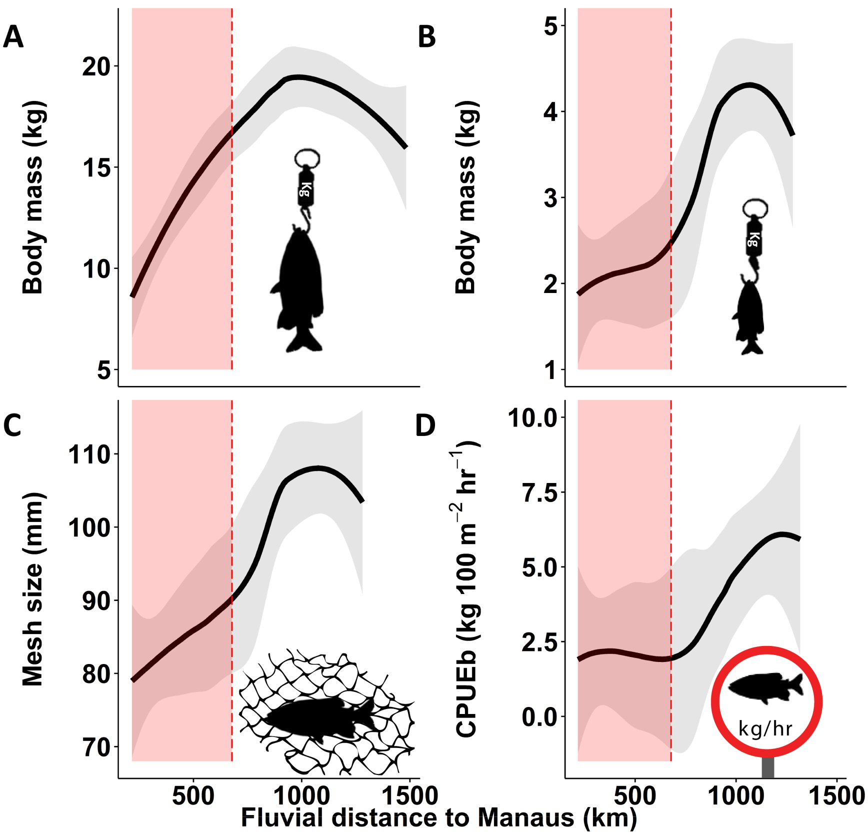

Fig. 2. Spatial declines in tambaqui (*Colossoma macropomum*) towards Manaus. Relationships between fluvial travel distance to Manaus and **(A)** the largest tambaqui caught in the fisher's lifetime (kg), **(B)** the mean sized tambaqui caught recently (kg), **(C)** the gill-net mesh size (mm) used to catch a tambaqui, and **(D)** tambaqui CPUEb (catch-per-unit-effort in biomass; kg per 100 m^2 of gill net and one hour of fishing). B to D represent fishing activity within 72 hours prior to interview. Red shaded areas depict the range in which fishers have regular access to fish-buyers and ice. Shown in grey are 95% confidence intervals.

tributaries with an undammed main channel, and the only one whose watershed remains wholly undammed (22).

Results

Spatial decline in tambaqui

Fishers nearer Manaus reported catching tambaqui half the size of those caught 1000 km from the city (Fig. 2*A* and *B*). The size of the largest tambaqui caught in the fisher's lifetime increased significantly with distance from Manaus (n = 392, P < 0.001), as did the mean size caught in the 72 hours prior to the interview (n = 51, P = 0.003). The tambaqui catch rate also doubled with increasing distance along the Manaus travel-distance gradient (Fig. 2*D*), with which a positive trend in CPUEb was found (n = 46, P = 0.035). Reductions in the gill net mesh size used to catch tambaqui were also found with increasing proximity to the city (n = 46, P = 0.002; Fig. 2*C*), indicating that fishers here do not expect to catch larger individuals.

Flooded forest cover was included as a model variable as it represents essential tambaqui feeding habitat, but showed no significant trends. Apart from distance to Manaus, the only significant variables in any of the four models showed a positive relationship between distance to the nearest town and the size of the largest tambaqui caught in in the fisher's lifetime (P = 0.022; Table S2), and a negative relationship between gillnet mesh size and human population density (P = 0.021). The slight dip in all four tambaqui population indices at greater distances from Manaus (Fig. 2) is likely explained by the presence of a road just upstream of our study area that connects this upper section of the Purus River to other distant urban markets.

Mechanism

The spatial decline in tambaqui nearer Manaus can be largely explained by frequent visits by boats from the city that buy fish. Field observations and our analytical results demonstrate that the fluvial gradient we surveyed can be split into two sub-systems. Commercial fishing is facilitated in rural communities closer to Manaus by boats that deposit ice and buy fish from local fishers at least once a week (shaded red in Figures 2*A* to *D*). Upstream of this, fishers sell fish independently when possible. Modelled trends of tambaqui capture from recent fishing activity (Figs. 2*B* to 2*D*) show clear inflection points, with steepening inclines in tambaqui demographic indicators upstream of regular fish-buyer routes. Communities receiving frequent visits from fish-buying boats reported the smallest tambaqui (largest in lifetime; $P < 0.001$, and mean in the 72 hours prior to interview; $P < 0.001$), the smallest mesh sizes used to catch them ($P < 0.001$), and the lowest CPUEb (P = 0.02; Fig. S3).

Ecosystem function

To estimate the potential ecological consequences of the smaller tambaqui body size on the Amazon's flooded forest, we simulated the impacts of over-harvesting tambaqui for seed dispersal by combining our mean body size data model (Fig. 2*B*) with a published model of median seed dispersal distance (25). When applied to our data, simulations predict that tambaqui 1350 km upriver from Manaus will disperse seeds twice as far (337 m) as those 300 km from Manaus (168 m).

Discussion

We present the first evidence of a large-scale spatially-dependent defaunation shadow around a rainforest metropolis, using the case of the tambaqui fishery around Manaus, home to more than two million people. Spatial declines in tambaqui body size, CPUEb and fishing net mesh size indicate that defaunation extends over 1000 km fluvial travel distance from the metropolitan market. Our findings have shown how these impacts are driven by urban demand for a high-value fish species (supported by *SI Results*), which also has a key role in the ecology of biodiversity-rich flooded forest and in the livelihoods of rural and urban Amazonians. We identify boats from Manaus buying fish as the principal mechanism explaining the spatial decline in tambaqui.

The strong spatial decline in the size of the largest tambaqui caught in the lifetime of fishers (Fig. 2*A*) indicates that Manaus has driven a spatially expanding depletion shadow of tambaqui. This sequential exploitation may well have started with the over-harvesting of fisheries near Manaus, followed by fish-buyers travelling further afield to find more intact tambaqui populations. Although the impacts of the growth of Manaus on the fishery are difficult to assess without modelling long-term data, our spatial-snapshot data provide strong evidence that fishing pressure driven by demand from Manaus has caused the depletion of tambaqui. This interpretation is supported by findings in the 1980s that CPUEn (catch-per-unit-effort in numbers) of tambaqui was lower in lakes nearer Manaus (26). Since then, however, Manaus has thrived economically and its population has doubled. According to official statistics, the resultant growing demand for tambaqui is mainly being met by a rapidly expanding aquaculture industry, while the reported wild catch has fallen. However, study of the Manaus fish market shows that the wild tambaqui landing data are vastly underestimated, due to widespread concealed landings of small wild tambaqui (27, 28) below the legal threshold (<55cm ≈ 4.3 kg), which consumers prefer to farmed individuals.

The spatially-dependent size-profile of tambaqui harvests is a key indicator of population status. Both within and across species, large-bodied animals tend to be the most impacted by wildlife consumption, because they are intrinsically vulnerable to over-harvesting (5, 8) and preferred by harvesters (higher returns on effort) and consumers (8), many of whom covet rarity (6). Urban consumers can therefore maintain strong demand for a small number of increasingly rare species (6), and are willing to pay high prices for large individuals.

This spatial decline in tambaqui size (Fig. 2) is highly likely to represent a gradient of socio-ecological impacts extending far from the metropolitan market center of Manaus. Economically, the loss of large tambaqui could be important, as larger individuals are the most valuable per kilogram, with larger fish (≥7kg) worth more than treble the price per kilogram to the fisher than the mean fish reportedly caught in this study (2.9kg) (Table S3). This is critically important in our study region because the primary source of rural earnings is selling fish (Fig. S4). Hence, the observed large-scale spatial declines are evidence that the unsustainable trade in tambaqui to Manaus may threaten long-term livelihood security hundreds of kilometers away, and could increase existing high reliance on conditional cash transfers as a main income source for many households (Fig. S4).

The loss of large freshwater fish species or size classes can trigger ecological cascades because they are often top apex predators with central roles in food web dynamics (8), or perform disproportionately important ecological functions, such as carbon flow modulation (29) and seed dispersal (30). Tambaqui can disperse seeds farther than almost any frugivorous animal yet studied, and this dispersal distance increases with body size (25). The major reductions in long-distance seed dispersal estimated in this study could inhibit the ability of tambaqui-dispersed seed species to germinate successfully, colonize unoccupied and distant patches and maintain gene flow across fragmented plant populations (25, 30, 31). However, while our simulations predict a spatial reduction in seed dispersal function caused by the observed defaunation, to truly understand the extent to which this will result in cascading changes to plant population and genetic diversity of the Amazonian flooded forest would require further work.

This study advances recent findings that anthropogenic impacts in terrestrial and marine systems are strongly determined by distance from cities (20) or market access (12–14). Our research therefore also contributes to evidence (7) refuting assertions that urbanization and resulting rural depopulation in the forested tropics will reduce harvesting impacts on biodiversity (32, 33). Finally, our findings may offer a warning for tropical Asia and Africa. While urbanization and the economy of the Amazon rainforest's main host nation (Brazil) currently surpasses that of the Congo (Democratic Republic of Congo) and Southeast Asian (Indonesia) rainforests, these regions are also experiencing rapid economic growth and urbanization (Fig. S2), which is likely to increase the defaunation shadows of rainforest cities there.

Methods

Study Area

The study was carried out in rural communities situated along the Purus River in the Brazilian Amazon (Fig. 1). The river offers a unique system to study overfishing in an otherwise relatively pristine environment. The Purus River supplies more fish to the Amazon's largest city, Manaus (population 2.1 million people; IBGE, 2010), than any other river (34–36). However apart from high fishing pressure, it does not suffer significantly from the other major threats of Amazonian freshwater degradation; deforestation, pollution and dam construction (21). The Purus River catchment meets the definition of a wilderness area (24), with high remaining forest cover, and low population densities (Table S1). It is the only major Amazonian tributary whose watershed remains undammed, and one of three with an undammed main channel (22).

Tambaqui was selected as our focal wildlife species both due to its socioecological importance, and because we believed that it presented us with the best chance of detecting overfishing induced spatial population trends, which are commonly masked in freshwater systems by a synergy of other pressures (21). Tambaqui is the most commercially valuable wild fish species in the region, and the most popular fish food species among our rural study population (Fig. S5) and Manaus residents (Fig. S6). It is also one of few Amazonian fish species thought to have witnessed wild stock declines (21, 37, 38); once being the most landed species in Manaus, but seeing dramatic declines in landed catch (38) and body size (39). Lastly, tambaqui has been identified as a high-quality seed disperser in the *várzea* flooded forest, and they disperse seeds longer distances than almost any frugivore (terrestrial or aquatic) reported in the literature (25).

Sampling

We worked downstream of the town of Lábrea and upstream from the confluence with the River Solimões. From the first to the last community the fluvial travel distance along the Purus River was 1267 km, as calculated using the travel network function in ArcGIS 10.2.2 (40). We would stop at the first community we came to as we travelled downstream from Lábrea that had 10-35 ordinarily (not necessarily currently) inhabited houses, and we would not stop at another community for a minimum of 13 km (mean 61 km) fluvial travel distance subsequently. Market access was indicated solely as fluvial travel distance to Manaus because the studied section of the Purus River contains no roads, and all transport is via the river network. We did not work in the stretch of the river covered by the Abufari Biological Reserve, as regulation and monitoring concerning harvesting practices were much more intense than in sustainable use reserves or unprotected areas, potentially causing unnecessary variation in results; both ecological, and in terms of response-bias.

We visited a maximum of 20 households per community. Where a community had more than 20 households, those to be visited would be selected randomly in a lottery system. We interviewed every household member of 16 years of age or older that had been fishing in the past 30 days (referred to as a fisher). Guided by average river levels (41), we visited each community at its approximate high water peak (April – July 2014) to reduce the variation in ecology and fisher activity caused by the flood pulse (42), thereby also avoiding working during the *defeso* fishing closed season.

Interview Questions

All fishers were asked in detail about the catch, effort and catch methods of every fishing trip that they had undertaken in the 72 hours prior to the interview. Where tambaqui was caught, they were asked to recall the number of individuals and estimated weight of the catch. To calculate effort, we asked fishers when they left and returned to their house, how long the return journey took, and how long they spent harvesting if they were not harvesting for the entire period that they were away from home and not travelling. For fishing net dimensions, we asked the mesh size (distance of the mesh between opposite knots in mm), length, and height. The length and height were used to calculate the net area. The largest fishing net mesh size used on a fishing trip that caught a tambaqui was used as a datapoint in the mesh size analysis as we do not know which net specifically caught tambaqui.

Use of interviews for collection of ecological data

There is a severe lack of data on harvesting of large and rare animals in rural tropical settings due to logistical difficulties, and due to difficulty in detection of such animals. Due to this, combined with the enormous geographical scale of the study area, this study required a much more efficient data collection method than standard scientific fish sampling. Interviews have been used increasingly in ecological studies to collect the knowledge of rural people, particularly harvesters. Compared to professional techniques, harvester CPUE (catch-per-unit-effort) has been shown to be much cheaper, more efficient, and result in similar levels of accuracy (43–46). One increasingly popular use of harvester interviews is the collection of catch and effort data, in order to undertake analyses on catch, effort, and CPUE. Commercial CPUE is probably the most widely used index of abundance in fisheries (47), and is being increasingly commonly used in studies freshwater fisheries (48–50).

Statistical Analysis

Statistical analyses were performed in R statistical software version 3.2.3 (51). Linear mixed models combining primary response variable data with secondary explanatory variable data were used for multivariate analyses. Response variables were quantitative responses to fisher surveys. Response variables were (1) the largest tambaqui individual caught by a fisher in their lifetime (kg), (2) the mean tambaqui caught by a fisher in the 72 hours prior to interview (kg), (3) the maximum gill net mesh size used on a fishing trip that caught tambaqui (mm), and (4) CPUEb in kg per 100 m^2 of net deployed, per hour it was in the water. To keep response variables spatially associated with each community's location, each response variable concerned only fishing trips that had occurred within 2 hours *rabeta* motorized canoe journey from the fisher's home in the community. This is a measure that local people can relate to and that is fairly standard, as most harvesting is undertaken using motorized canoes of similar power (generally 5.5 horse-power) that travel at around 9 km h^{-1} (19). Community was used as a random variable in all models. Model diagnostic plots were subsequently inspected.

Explanatory variables were fluvial distance from Manaus (km), fluvial distance from the closest town (Lábrea, Canutama, Tapauá or Beruri) (km), human population density (people per km^2), and percentage flooded forest (*várzea*) cover within a 5 km radius of the community. Human population density was calculated as the 2010 Brazilian census population of the census sector in which the relevant community was located (23), divided by the area of that census sector (calculated in ArcMap (40)).

Percentage flooded forest area was included because most tambaqui were caught in the flooded forest, which is an essential tambaqui feeding habitat (28). To calculate this we initially made a flooded forest map of the study area in ArcMap (40), which consisted of the area defined as forest (TerraClass landcover map (52)) that spatially coincided with the area that is permanently or seasonally flooded (floodplain map). A buffer with a 5 km radius was then created around each community, and the percentage of this area covered by flooded forest was calculated. This percentage ranged between 16.3-92.2% (mean 59.0%), but a linear model found that there was no significant trend with distance to Manaus ($P = 0.5$). We also performed a linear model to explore the possibility of a trend in the age of the sampled tambaqui fishers and distance to Manaus in case this could influence results, and also found no significant trend ($P = 0.25$).

Ethics

On arrival to every community we would initially approach the principal community representative (*presidente*) to thoroughly explain the research and ask permission to work in the community. A further explanation of the research was given on arrival at every interviewed household. Oral permission was obtained before proceeding with research, which was seen as more ethically sound than written permission in an area with high illiteracy rates. The research was assessed and approved by ethics committees at both Lancaster University (UK) and the Federal University of Lavras (Brazil). Article 37 of Brazilian law 9605 from 1998 states that killing an animal is not a crime when it is carried out to satisfy the hunger of the harvester or their family. At no point in this paper was it stated whether any of the sampled fish were sold or used for consumption, and therefore no activity presented in this paper can be perceived as illegal.

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1. Dirzo R, Raven PH (2003) Global State of Biodiversity and Loss. *Annu Rev Environ Resour* 28(1):137–167.
2. Sans P, Combris P (2015) World meat consumption patterns: An overview of the last fifty years (1961–2011). *Meat Sci* 109:106–111.
3. Foley JA, et al. (2005) Global Consequences of Land Use. *Science (80-)* 309(5734):570–574.
4. Béné C, et al. (2015) Feeding 9 billion by 2050 - Putting fish back on the menu. *Food Secur* 7(2):261–274.
5. Milner-Gulland EJ, Bennett EL (2003) Wild meat: the bigger picture. *Trends Ecol Evol* 18(7):351–357.
6. Shairp R, Veríssimo D, Fraser I, Challender D, Macmillan D (2016) Understanding urban demand for wild meat in Vietnam: Implications for conservation actions. *PLoS One* 11(1):e0134787.
7. Parry L, Barlow J, Pereira H (2014) Wildlife Harvest and Consumption in Amazonia's Urbanized Wilderness. *Conserv Lett* 7(6):565–574.
8. Allan JD, Abell R, Hogan Z, Revenga C (2005) Overfishing of inland waters. *Bioscience* 55(12):1041–1051.
9. Dirzo R, et al. (2014) Defaunation in the Anthropocene. *Science (80-)* 345(6195):401–406.
10. McCauley DJ, et al. (2015) Marine defaunation: Animal loss in the global ocean. *Science (80-)* 347(6219):247–254.
11. Scales H, Balmford A, Liu M, Sadovy Y, Manica A (2006) Keeping bandits at bay. *Science (80-)* 313(4 August 2006):612–613.
12. Cinner JE, et al. (2016) Bright spots among the world's coral reefs. *Nature* 535(7612):416–419.
13. Maire E, et al. (2016) How accessible are coral reefs to people? A global assessment based on travel time. *Ecol Lett* 19:351–360.
14. Brewer TD, Cinner JE, Green A, Pandolfi JM (2009) Thresholds and multiple scale interaction of environment, resource use, and market proximity on reef fishery resources in the Solomon Islands. *Biol Conserv* 142(8):1797–1807.
15. Castello L, Mcgrath DG, Beck PS a. (2011) Resource sustainability in small-scale fisheries in the Lower Amazon floodplains. *Fish Res* 110(2):356–364.
16. Fa JE, et al. (2010) Impact of Market Hunting on Mammal Species in Equatorial Guinea. *Conserv Biol* 9(5):1107–1115.
17. Wilkie DS, Carpenter J (1999) Bushmeat hunting in the Congo Basin: an assessment of impacts and options for mitigation. *Biodivers Conserv* 8:927–955.
18. Allebone-Webb S, et al. (2011) Use of market data to assess bushmeat hunting sustainability

in Equatorial Guinea. *Conserv Biol* 25(3):597–606.
19. Parry L, Peres CA (2015) Evaluating the use of local ecological knowledge to monitor hunted tropical-forest wildlife over large spatial scales. *Ecol Soc* 20(3):15.
20. Ahrends A, et al. (2010) Predictable waves of sequential forest degradation and biodiversity loss spreading from an African city. *Proc Natl Acad Sci* 107(33):14556–14561.
21. Castello L, et al. (2013) The vulnerability of Amazon freshwater ecosystems. *Conserv Lett* 6(4):217–229.
22. Winemiller KO, et al. (2016) Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science (80-)* 351(6269):128–129.
23. IBGE (2010) *Censo Demográfico 2010* (Rio de Janeiro, Brazil) Available at: http://www.ibge.gov.br/home/estatistica/populacao/censo2010/default.shtm.
24. Mittermeier RA, Myers N, Thomsen JB, da Fonseca GAB, Olivieri S (1998) Biodiversity Hotspots and Major Tropical Wilderness Areas: Approaches to Setting Conservation Priorities. *Conserv Biol* 12(3):516–520.
25. Anderson JT, Nuttle T, Saldaña Rojas JS, Pendergast TH, Flecker AS (2011) Extremely long-distance seed dispersal by an overfished Amazonian frugivore. *Proc R Soc B Biol Sci* 278(1723):3329–3335.
26. Petrere Jr. M (1986) Amazon fisheries I - Variations in the relative abundance of Tambaqui (Colossoma macropomum CUVIER, 1818) based on catch and effort data of the gill-net fisheries. *Amazoniana* 9(4):527–547.
27. Santos GM, Ferreira EJ, Zuanon JA (2006) *Peixes Comerciais de Manaus* eds Santos GM, Ferreira EJ, Zuanon JA (ProVárzea, Manaus).
28. Araujo-Lima CARM, Goulding M (1997) *So fruitful a fish: Ecology, conservation and aquaculture of the Amazon's tambaqui* (Columbia University Press, New York).
29. Taylor B, Flecker AS, Hall Jr R (2006) Loss of a Harvested Fish Species Disrupts Carbon Flow in a Diverse Tropical River. *Science (80-)* 313(11):833–836.
30. Correa SB, et al. (2015) Overfishing disrupts an ancient mutualism between frugivorous fishes and plants in Neotropical wetlands. *Biol Conserv* 191:159–167.
31. Anderson JT, Rojas SJ, Flecker AS (2009) High-quality seed dispersal by fruit-eating fishes in Amazonian floodplain habitats. *Oecologia* 161(2):279–290.
32. Aide TM, Grau HR (2004) Ecology. Globalization, migration, and Latin American ecosystems. *Science (80-)* 305:1915–1916.
33. Wright SJ, Muller-Landau HC (2006) The Future of Tropical Forest Species. *Biotropica* 38(3):287–301.
34. Cardoso RS, Batista VDS, Henry C, Júnior F, Martins WR (2004) Aspectos econômicos e operacionais das viagens da frota pesqueira de Manaus, Amazônia Central. *Acta Amaz* 34(2):301–307.
35. Gandra A (2010) *O mercado de pescado da região metropolitana de Manaus* (INFOPESCA, Montevideo).
36. Batista VDS, Petrere Júnior M (2003) Characterization of the commercial fish production landed at Manaus, Amazonas State, Brazil. *Acta Amaz* 33(1):53–66.
37. Isaac VJ, Ruffino ML (1996) Population dynamics of tambaqui, Colossoma macropomum Cuvier, in the Lower Amazon, Brazil. *Fish Manag Ecol* 3(4):315–333.
38. Merona B, Bittencourt MM (1988) A pesca na Amazônia através dos desembarques no mercado de Manaus: resultados preliminares. *Soc Ciencias Nat La Salle*:433–453.
39. Costa-Pereira R, Galetti M (2015) Frugivore downsizing and the collapse of seed dispersal by fish. *Biol Conserv* 191:809–811.
40. ESRI (2014) ArcMap 10.2.2. Available at: www.esri.com/software/arcgis.
41. Coe MT, Costa MH, Botta A, Birkett C (2002) Long-term simulations of discharge and floods in the Amazon Basin. *J Geophys Res Atmos* 107(20):1–17.
42. Junk WJ, Bayley PB, Sparks RE (1989) The flood pulse concept in river-floodplain systems. *Can Spec Publ Fish Aquat Sci* 106(1):110–127.
43. Rist J, Milner-Gulland EJ, Cowlishaw G, Rowcliffe JM (2010) Hunter Reporting of Catch per Unit Effort as a Monitoring Tool in a Bushmeat-Harvesting System. *Conserv Biol* 24(2):489–99.
44. Jones JPG, Andriamarovololona MM, Hockley N, Gibbons JM, Milner-Gulland EJ (2008) Testing the use of interviews as a tool for monitoring trends in the harvesting of wild species. *J Appl Ecol* 45(4):1205–1212.
45. Tesfamichael D, Pitcher TJ, Pauly D (2014) Assessing changes in fisheries using fishers' knowledge to generate long time series of catch rates: A case study from the red sea. *Ecol Soc* 19(1). doi:10.5751/ES-06151-190118.
46. Grant S, Berkes F (2007) Fisher knowledge as expert system: A case from the longline fishery of Grenada, the Eastern Caribbean. *Fish Res* 84(2):162–170.
47. Edwards CTT, Hillary RM, Levontin P, Blanchard JL, Lorenzen K (2012) Fisheries Assessment and Management: A Synthesis of Common Approaches with Special Reference to Deepwater and Data-Poor Stocks. *Rev Fish Sci* 20(3):136–153.
48. Almeida OT, Lorenzen K, Mcgrath DG (2002) Impact of Co-Management Agreements on the Exploitation and Productivity of Floodplain Lake Fisheries in the Lower Amazon. *Proceedings of the 9th Biennial Conference of the International Association for the Study of Common Property*, p 12.
49. Hallwass G, Lopes PF, Juras A a., Silvano RAM (2011) Fishing effort and catch composition of urban market and rural villages in Brazilian Amazon. *Environ Manage* 47(2):188–200.
50. Pinho PF, Orlove B, Lubell M (2012) Overcoming barriers to collective action in community-based fisheries management in the Amazon. *Hum Organ* 71(1):99–109.
51. R Core Team (2015) R: A language and environment for statistical computing. Available at: https://www.r-project.org/.
52. Instituto Nacional de Pesquisas Espaciais (INPE) (2010) Dados TerraClass 2014. Available at: http://www.inpe.br/cra/projetos_pesquisas/terraclass2014.php.
53. Batista V da S, et al. (2012) *Peixes e pesca no Solimões-Amazonas: uma avaliação integrada* (Brasilia).
54. Pesquisa365 (2015) *Consumo365* (Manaus) Available at: http://www.slideshare.net/pesquisa365/consumo365.
55. IBGE (2009) POF (Pesquisa de Orçamentos Familiares 2008-2009). *Análise do Consum Aliment Pessoal no Bras*. Available at: http://www.ibge.gov.br/home/estatistica/populacao/condicaodevida/pof/2008_2009_analise_consumo/default.shtm.
56. UN (2015) World Population Prospects: The 2015 Revision. Available at: https://esa.un.org/unpd/wpp/.
57. International Monetary Fund (2016) World Economic Outlook Database. Available at: https://www.imf.org/external/pubs/ft/weo/2016/01/weodata/index.aspx.
58. Saatchi SS, et al. (2011) Benchmark map of forest carbon stocks in tropical regions across three continents. 108(24). doi:10.1073/pnas.1019576108.
59. Instituto Nacional de Pesquisas Espaciais (INPE) (2014) PRODES: Desflorestamento nos Municípios da Amazônia Legal para o ano de 2014. Available at: http://www.dpi.inpe.br/prodesdigital/prodesmunicipal.php.