Demography-based management of a lake meta-population network boosts food security in Amazonian fisheries

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Abstract

Global demand for natural resources challenges the sustainability of small-scale fisheries. Fisheries Co-Management (FCM), where management is shared between the government and locals, is crucial for maintaining viable fish populations while mitigating market pressures and illegal fishing. Using a data-informed model applied to a fish metapopulation network, we contrasted the effects of various FCM scenarios on the abundance of Arapaima (*Arapaima gigas*) populations—a key income source for Amazonian communities—across 13 protected and 18 unprotected lakes in the Juruá River Basin, Brazilian Amazon. Our results show that the current FCM scheme is suboptimal and could be improved by protecting lakes based on their carrying capacity, which enhances population resilience in protected lakes and maintains stocks in unprotected ones. Lakes interconnectivity also plays a key role in sustaining regional metapopulation dynamics. Expanding FCM practices across the Amazon requires integrating local knowledge with scientific evidence to support biodiversity and local well-being.

Significance

To secure a healthier future for Amazonia, integrating biodiversity protection with human wellbeing is crucial. Fisheries are vital for food security and income, yet they are constantly threatened by overharvesting, jeopardising sustainable practices. Effective management relies on collaboration between local communities and scientists to optimise resource use. We present a network-based dynamic modelling approach that incorporates local knowledge and field data to provide a flexible tool for decision-making in complex socio-ecological systems. This is particularly relevant for Fisheries Co-Management schemes, where ecological resilience and economic needs must be balanced. We show that a demographic-based scenario boosts food security and supports the Amazon's largest freshwater fish recovery, attesting that population recovery of emblematic megafauna aligned with people's wellbeing is possible.

Key-words: Amazon conservation; freshwater fish ecology; metapopulation dynamics; socio-ecological systems; spatial networks

Introduction

Ecosystem services (ES) provided by freshwater systems are crucial for food security, health, and wellbeing[1–3]. The increasing demand for natural resources leads to unsustainable practices that deteriorate habitats and biodiversity, essential for a healthy human-nature relationship[2,4]. Mitigating the challenges imposed on natural ecosystems by unsustainable human exploitative practices can be achieved in multiple ways, but often fit within two broad categories. Top-down regulations enforce conservation through protected areas and resource exploitation limits, or quotas[5,6], while participatory initiatives such as Collaborative Management (Co-Management) aim at involving local communities in the decision-making process of natural resource uses[7,8].

Fisheries have historically provided a fundamental ES but are constantly threatened by overharvesting and vulnerable to various threats, from market fluctuations to climate change[9]. Recent research on small-scale fisheries emphasises the importance of integrating ecological and social dimensions to move towards sustainable practices[10,11]. In that sense, Fisheries Co-Management (FCM) schemes, in which local people and governmental entities cooperate, are particularly effective. Incorporating local knowledge empowers local communities, while enhancing compliance with top-down regulation and environmental justice[12,13]. Regional coordination among fishers is essential as fish populations form a common-pool resource system. Communication between individual fishers exploiting fisheries in the same local areas has proven effective, especially when multiple catch species are available[14,15]. However, challenges arise when fishers rely on one or few species critical to their income. Avoiding overfishing and the tragedy of the commons depends on the interplay between fish biology, fishing pressure, management schemes, and the fish’s metapopulation network.

Understanding the impact of management decisions on ES provision is challenging due to the intricate interplay within and between ecological (e.g. populations and communities) and human (e.g. social groups and organisations) systems[16,17]. Adopting a networked systems perspective in which entities (ecological, social, or both) are embedded in a web of interactions is ideal for addressing the dependencies and feedback loops typical of social-ecological systems[18,19]. However, most ES-focused network studies overlook the dynamic processes (e.g. fish flow) underlying these networks[16,18]. This gap makes it difficult to quantitatively assess the outcomes of management decisions applied to ES networks at a regional level. Addressing this gap is particularly important for developing sound co-management schemes that make resource harvesting sustainable while at the same time benefiting local communities whose livelihoods depend on these resources.

We explore the FCM conservation program of the Arapaima (*Arapaima gigas* (Cuvier, 1829)) in the Middle Juruá River Basin, Western Brazilian Amazon (Fig 1). Arapaima is the world's largest freshwater fish, nationally and internationally protected against overfishing[20–22], and a major income source for local fishery communities. Its floodplain ecosystem is characterised by seasonal flooding during which they move along the main river and among areas that otherwise remain isolated during the dry season. This flooding pattern creates a metapopulation network with seasonal dynamics across the main river and its associated lakes.

The protection of lakes by FCM has been instrumental to the recovery of the historically overfished Arapaima[23,24]. It contributes to avoiding further fish stock crashes and ensures an opportunity to enhance the income of fishers and their families[25,26]. This successful initiative has encouraged participation by entire communities, particularly women, fostering cooperation between remote rural villages and strengthening regional associations[12]. Due to its successful social and ecological outcomes, the Arapaima FCM is recognized as one of the most promising grassroots initiatives to tackle conservation, food security, and poverty challenges across the Amazon[12,26]. However, lake protection is costly and time-consuming for fishing communities, involving expenses for fuel, food, and opportunity costs during surveillance patrols. Thus, while successful, the optimal management scheme – specifically, which lakes to protect and what are the social, economic, and ecological attributes that define the success of this scheme — remains unclear.

To address this issue, we developed a process-based dynamical model[27] parameterized with empirical FCM data to assess the effects of several small-scale fishing schemes on the persistence (i.e. sustainability) of the Arapaima metapopulation formed by interconnected habitat lakes. Links in the network represent dispersal routes for Arapaima, allowing migratory fish to establish populations in new lakes and adults to return to their ‘original’ lake[28] (Fig 1).

We compare a set of hypothesis-driven FCM scenarios to quantify their impact at the regional, riverscape scale and at the local, lake scale. Across scenarios, lakes (i.e., local habitat patches in the metapopulation) can be protected or unprotected by FCM, and managed according to governmental top-down regulatory policies of fishing quotas. Protected and unprotected lakes respond differently to fluctuations in legal and illegal fishing. Protected lakes support higher Arapaima populations[23] and buffer against increased fishing pressure due to high return rates of adult Arapaima[28,29]. Unprotected lakes are particularly susceptible to illegal and unregulated fishing because of the lack of both top-down and bottom-up regulations[30]. They can, therefore, experience the collapse of their Arapaima population, as the immigration of new individuals is limited. We contrast the current FCM scheme with six other lake protection scenarios based on network topology, lake characteristics, and geography (Table 1). We show that the current FCM scheme is suboptimal for unprotected lakes and can be improved by implementing a scheme based on Arapaima lakes’ carrying capacity. Additionally, FCM effectiveness is highly influenced by illegal fishing quotas in a non-linear fashion.

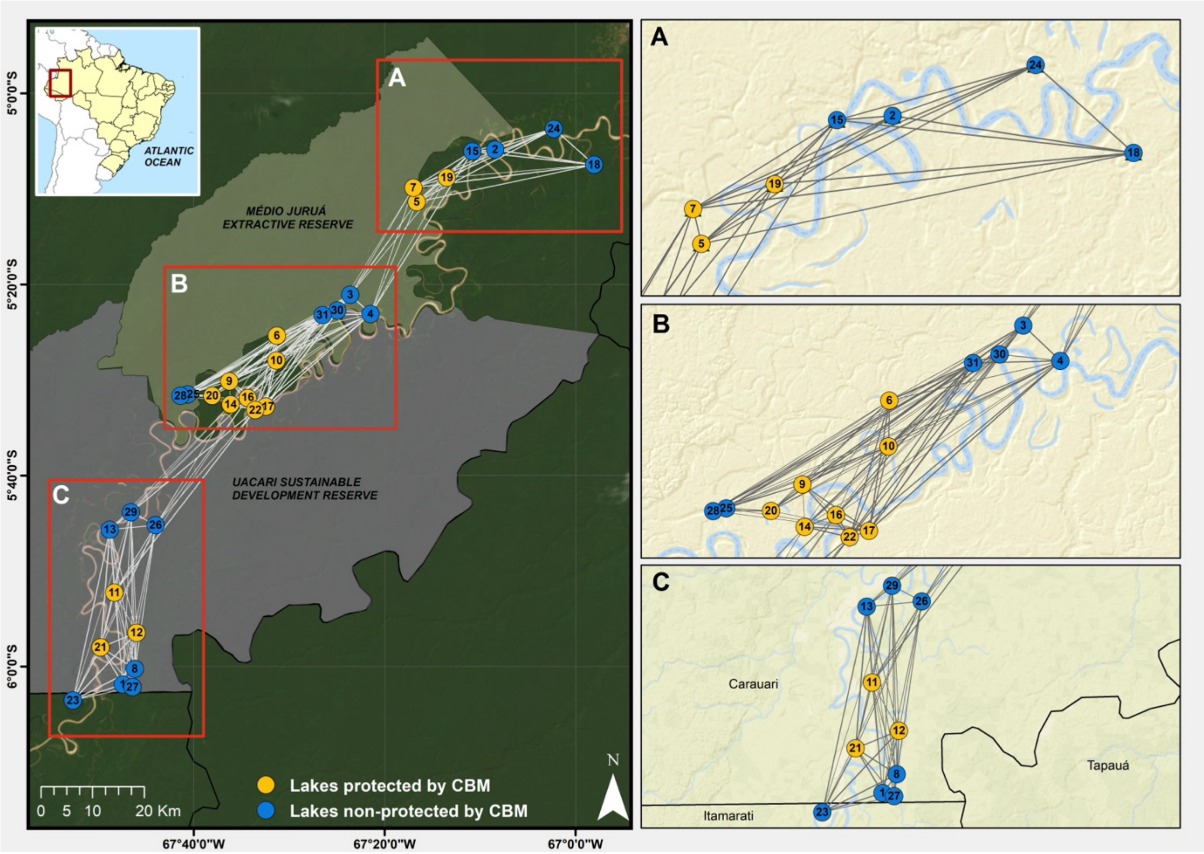

Figure 1. Study area and the metapopulation network of the Arapaima (*Arapaima gigas*) at the Middle Jurua River Basin, Western Brazilian Amazon. Each lake is a node in the network and is represented by a number; the list of lakes and their attributes can be found in Table S1. The position of each lake represents its latitude/longitude coordinates along the Juruá River. Links between nodes indicate whether two lakes are spatially connected by Arapaima movement during the flooding season. Network construction is described in the Methods. Panels A, B, and C zoom in on the study area's north, central, and south regions, respectively, showing detailed connections among protected (yellow nodes) and unprotected lakes (blue nodes) performed by the Arapaima movement. Undirected links are shown for clarity. We used ArcGIS and Arcmap 10.825 to draw the map layout.

Table 1. Description of the management scenarios used to assess the potential consequences of increasing fishing pressure on the abundance and persistence of Arapaima (*Arapaima gigas*) at the Middle Juruá River Basin, Western Brazilian Amazon. We compare the current FCM scheme (business-as-usual) to five hypothesis-driven alternative management scenarios and randomness (random protection scenario with no criteria). Note that in each scenario, we fix the number of protected lakes to 13, as in the current FCM. See Table S2 for the list of protected lakes in each scenario.

Protection scenario	**Hypotheses**	**Analyses**
1. Business-as-usual	**H1:** Current FCM scheme, which is based on the number of fish per lake and lake's distance to the main river, is optimal. However, increasing legal and illegal fishing quotas lead to system collapse, which is faster in unprotected lakes[30].	Keep the same 13 protected lakes as the current empirical protection scheme while increasing fishing effort for both protected and unprotected lakes.
2. Protect the most connected lakes	**H2:** The most connected lakes serve as a 'source' of Arapaima for the metapopulation dynamics at the riverscape scale[18,19]. Therefore, their protection would increase the abundance of Arapaima at the metapopulation level.	Protect the 13 lakes with the highest strength (sum of dispersal link weights)[31,32], given the empirical metapopulation network.
3. Protect the least connected lakes	**H3:** Because Arapaima tend to return to protected lakes[28,29], protecting the less connected lakes would facilitate its establishment in more isolated areas of the network, improving riverscape connectivity, facilitating migration and conserving higher-risk populations.	Protect the 13 lakes with the lowest strength (sum of dispersal link weights)[31,32], given the empirical metapopulation network.
4. Protect larger	**H4:** Larger lakes can sustain larger	Protect the 13 lakes with

lakes	populations of arapaima as their niche space is greater in terms of food resources and reproductive sites[33,34]. Therefore, larger lakes can serve as a ‘source’ of Arapaima in the metapopulation dynamics.	the largest area (ha).
5. Protect lakes with higher carrying capacity	**H5:** Lakes with higher carrying capacity would function as a source of arapaima fish, which then can disperse to safe sites and maintain overall positive growth rate[35].	Protect the 13 lakes with the highest carrying capacity.
6. Protect lakes according to their geographic position	**H6:** Protecting farther away lakes would help maintain population abundance and increase metapopulation connectivity by lowering illegal fishing[23] and buffering against external pressures.	Protect the six northernmost and the seven southernmost lakes because these are more vulnerable to illegal fishing coming from outside Protected Areas.
7. Protect lakes randomly	**H7:** Protecting lakes with no biotic or abiotic criteria would lead to local population collapses and lowest metapopulation persistence.	Randomly select 13 lakes to protect.

Results

The Arapaima metapopulation network had 338 links among the 31 lakes (13 protected, 18 unprotected), with a density (proportion of realised links) of 0.36. Total node degree averaged 21.8 (± 6.01). Lake out-strength centrality (the sum of a lake's outgoing links), which is a measure of a lake's importance for riverscape connectivity (used in scenarios 2 and 3), varied from 0.17 to 0.43 (mean = 0.32 ± 0.07) (Table S1; see Fig S1 for node and out-strength distribution).

We identified the determinants of Arapaima population abundance using linear regression within a model selection framework. We considered the following fixed effects: (i) scenario, (ii) protection status, (iii) fishing effort, and the pairwise interactions between each of these variables and included lake as a random effect to account for the non-independence of observations from the same lake (Methods). Arapaima abundance was significantly affected by lake protection status, scenario, fishing effort, and their statistical interactions (Table 2, Table S3). Lake protection had a positive effect on Arapaima population abundance across all scenarios above the 0.3 fishing quota; below that, the Arapaima population was equal, or even higher, in unprotected lakes (Tukey post hoc test on the protection and scenario fixed effects; Fig 2; Table S4).

Overall, increasing fishing effort significantly reduced the average population of Arapaima across scenarios for unprotected lakes (Fig 3; Table S5). The expected adverse effect of fishing on protected lakes was buffered by the 0.3 maximum quota established in FCM-protected lakes. Maintaining this quota allowed the Arapaima population to remain stable in protected lakes in all scenarios, even under high fishing pressure in unprotected lakes. Yet, the scenario based on carrying capacity (H5) consistently showed the highest population of Arapaima, followed by business-as-usual (H1) (Fig 3).

Furthermore, protecting lakes with the highest carrying capacity (H5) showed the lowest overall difference in Arapaima population abundance between protected and unprotected lakes (Est = -0.10, SE = 0.03, t = -3.00; Fig 2; Table S4), generating a better balance between protected and unprotected lakes at the riverscape scale. Similar to business-as-usual (H1), protecting lakes under carrying capacity scenario

(H5) proved efficient for unprotected lakes under higher fishing efforts because the magnitude of the decline in the Arapaima population was less abrupt than in other scenarios (Fig 3; Table S3). Interestingly, the carrying capacity and the business-as-usual scenarios showed the highest differences between protected and unprotected lakes at low fishing pressure (<0.4), in which unprotected lakes had more Arapaima than protected ones (Fig S2, Table S5). Conversely, the difference between protected and unprotected lakes is relatively lower at higher fishing effort (>0.3) in both cases (Fig S2).

Arapaima population in unprotected lakes was similar among scenarios at low fishing effort (<0.3); differences among scenarios were only noticeable at high fishing efforts (Fig 3). The system started to collapse at intermediate levels (>= 0.6) of fishing effort for the most connected (H2), least connected (H3) and the geography (H6) scenarios (Fig 3, Table S5). Randomly protecting lakes was generally less efficient than implementing a purposely designed management scheme, highlighting the importance of decision-making in FCM (Fig 3).

Table 2. Results from the Linear Mixed Model showing the effects of lake protection, management scenario and fishing effort as well as the interactions among them on the population of Arapaima (*Arapaima gigas*) at Middle Juruá River Basin, Western Brazilian Amazon. The full model was selected as the best model according to Akaike Information Criteria (LogLik = -420, Delta = 0, AICc = 888.4, weight = 1); therefore only the results of this model are shown. The full model: log10(pop.means + 1) ~ scenario + protected + fishing_effort + scenario:protected + protected: exploitation_effort + scenario:fishing_effort + (1 |lake)

	Sum Sq	**Mean Sq**	**DF**	**F value**	**Pr(>F)**
Fishing effort	203.362	203.362	1.000	2805.678	0
Protected	31.745	31.745	1.000	437.973	3.39E-90
Scenario	4.434	0.739	6.000	10.195	3.52E-11
Fishing effort:protected	125.151	125.151	1.000	1726.649	1.20E-291
Fishing effort:scenario	6.502	1.084	6.000	14.951	6.82E-17
protected:scenario	8.514	1.419	6.000	19.576	1.79E-22

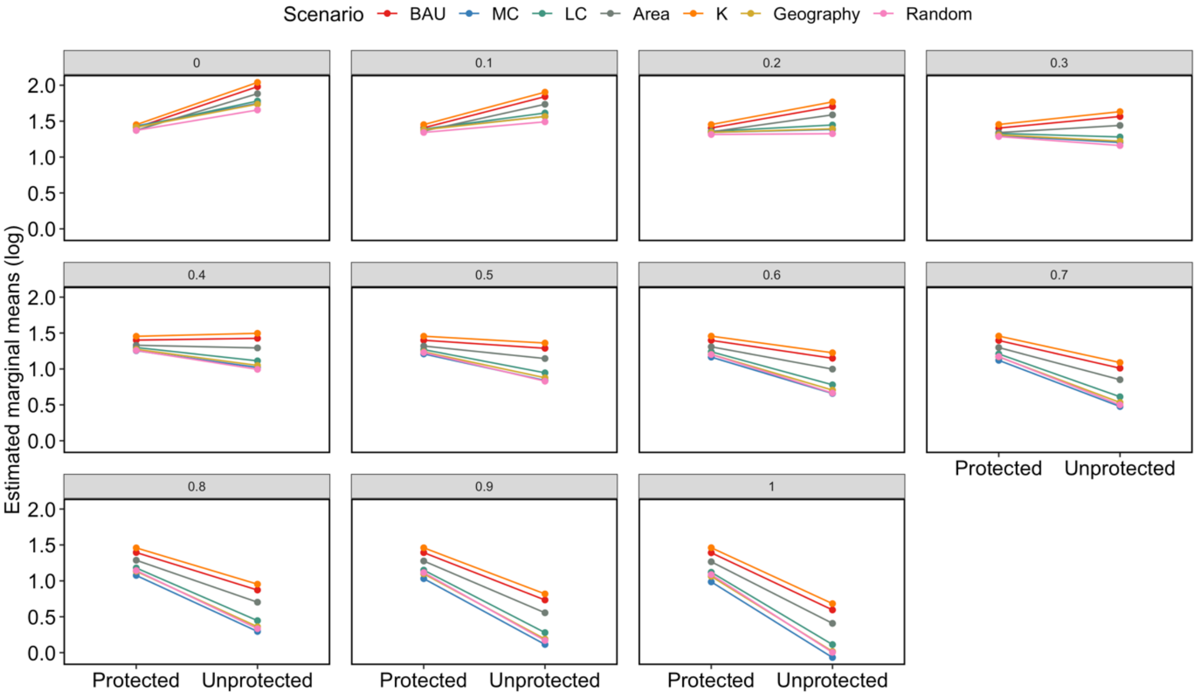

Figure 2. The effect of protection and fishing quota on Arapaima abundance. Each data point is the Estimated Marginal Means of log fish abundance, calculated from the statistical model and adjusted according to the other variables in the model, for protected and unprotected lakes. Each line represents the change in the Estimated Marginal Means for a specific scenario. Colours represent the Fishery Co-Management (FCM) scenarios (Table 1). Each panel is a fishing quota with quotas above 0.3 considered illegal fishing.

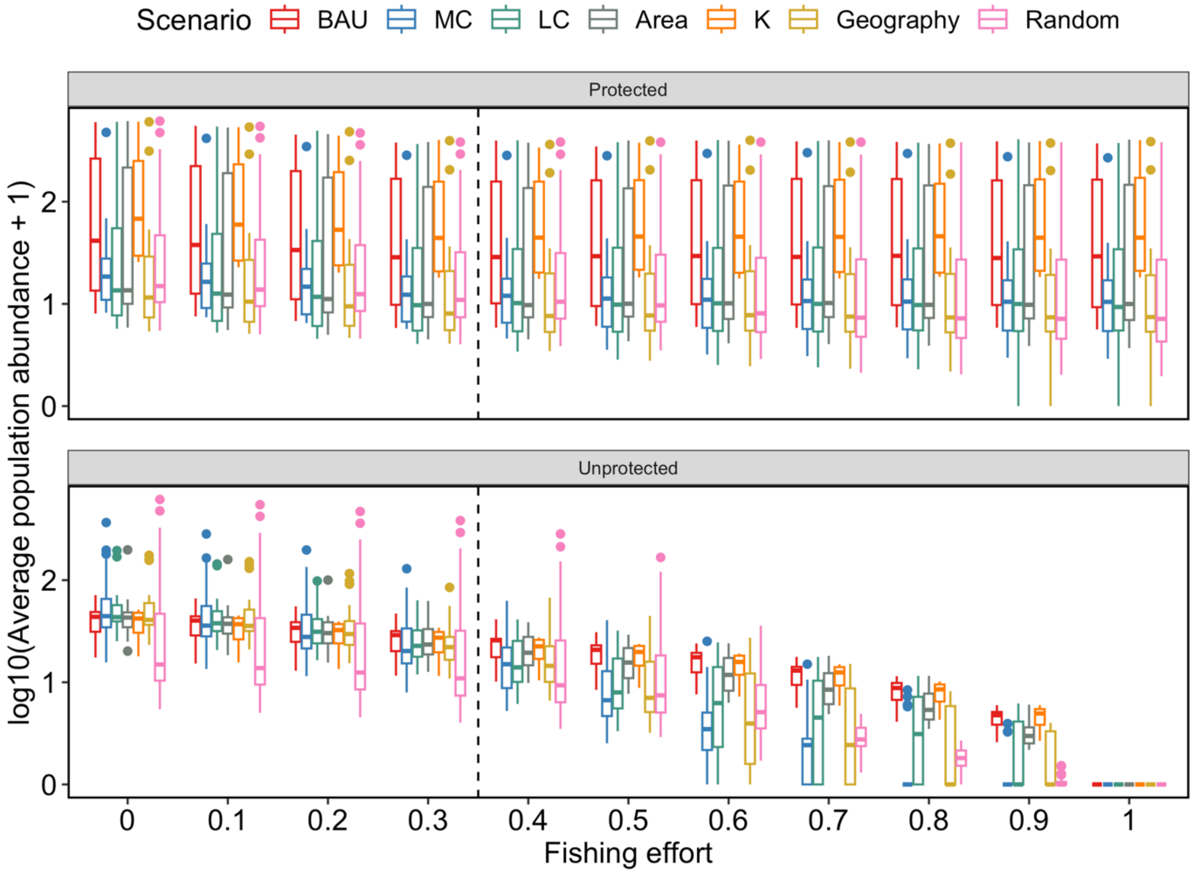

Figure 3. Effects of fishing effort across scenarios for protected and unprotected lakes. The plots show the average population abundance (log scale) across scenarios and increasing fishing pressure for protected and unprotected lakes. Vertical dashed lines mark the maximum fishing quota allowed by governmental authorities for lakes within the FCM. Fishing efforts to the right of the line are considered illegal. Thus, in protected lakes, the fishing effort to the right of the line is always 0.3, meaning that protected lakes are not fished for more than 30% of their Arapaima population in any scenario. Each data point represents a lake; therefore each boxplot shows the median of population abundance (log10) across the 31 studied lakes, the minimum and maximum values, the first and third quartile of data distribution, and the outliers. Simulations were run for 50 time steps for each scenario. The abundance value of each point is the average abundance over the last 10 time steps. The legend of the scenarios correspond to: BAU - Business-as-usual (H1); MC - Protecting most connected lakes (H2); LC - Protecting least connected lakes (H3); Area - Protecting larger lakes (H4); K - Protecting lakes with higher carrying capacity (H5); Geography - Protecting lakes according to geographic position (H6); Random - Protecting lakes randomly (H7). See Table 1 for details of each scenario.

Persistence at the metapopulation level

The choice of management scenario also has implications for the regional riverscape persistence of the Arapaima metapopulation (Fig 4). Our temporal data showed that in the initial years of FCM lakes that had very few individuals (e.g., Onça and Santo Antônio), or even none (Janiceto) still recovered with the initiation of FCM initiatives (Table S6; Fig S3, S4). Therefore, we first considered qualitative persistence (i.e., the proportion of lakes with non-zero Arapaima). While business-as-usual (H1), area (H4) and carrying capacity (H5) scenarios performed similarly, the most and least connected (H2, H3) and geography (H6) (Fig 4, left panel) generated a faster collapse, starting at a fishing quota of 0.5. For the more robust scenarios, Arapaima populations went extinct at the riverscape level above a 0.9 fishing effort.

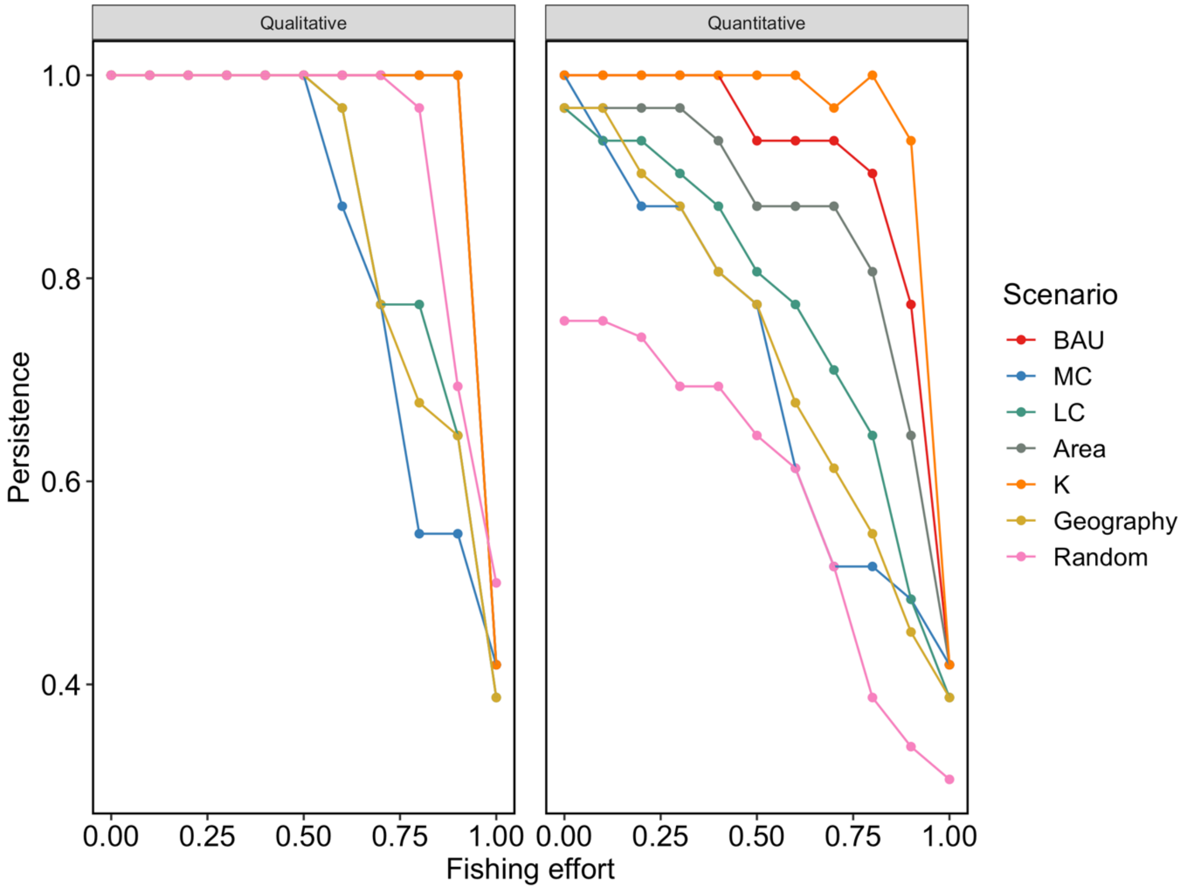

Figure 4. Effect of fishing effort on Arapaima metapopulation persistence. The plots show the proportion of lakes persisting at the metapopulation level across increasing fishing pressure for the seven simulated scenarios (Table 1). Qualitative persistence (left panel) considers a lake to persist in the metapopulation if the Arapaima abundance is > 0. Quantitative persistence (right panel) considers

that a given lake persists in the system only if Arapaima abundance is at least half of the carrying capacity of that lake.

We additionally quantified persistence at the metapopulation level as the proportion of lakes remaining in the riverscape with a population abundance of Arapaima >= half of the lake's carrying capacity (K) (Fig 4, right panel). This way of assessing metapopulation persistence considers that viable populations should be large enough to be resilient to stochastic extinctions and maintain large enough numbers in the long term. The carrying capacity (H5) emerged as the best scenario as the metapopulation better withstands harvesting when compared to other cases The current FCM was the second-best scenario as lakes started disappearing from the riverscape when reaching a 0.5 fishing effort. A random choice of lake protection (H7) performed the worst, as even in the lack of fishing, only about 80% of the lakes persist, indicating that protecting lakes without any criteria is also ineffective at the riverscape level. The metapopulation does not entirely collapse in any scenario as some lakes remain in the system (around 40% persistence overall). This is likely due to the positive growth rate applied to our models, which maintains new individuals arriving after harvesting.

Discussion

The increasing demand for natural resources drives unsustainable practices that degrade ecosystems and undermine their services. Effective mitigation requires collaboration between local communities and scientists to assess resource exploitation within socio-ecological systems. We provide insights into the interplay between resource use and ecosystem services by integrating local knowledge, natural history, ecological data, network theory, and computational modelling.

Given the complexity of social-ecological systems, empirically testing management scenarios is impractical. Therefore, holistic models like ours, which integrate various socio-ecological factors, are valuable for identifying optimal configurations and informing decision-making[9,10]. Historically, Juruá fishers have selected lakes for protection through trial and error, like many small-scale fisheries[10]. This strategy is represented by the random scenario, showing that protection without any criteria is the least effective scheme. Nowadays, experienced fishers choose FCM lakes based on area, capacity, and proximity to the main river (JV Campos-Silva, pers. knowledge). Our findings suggest that the current FCM scheme is suboptimal and could be improved by protecting lakes based on their carrying capacity. This approach would boost Arapaima populations in protected lakes and maintain stocks in unprotected lakes, optimising source-sink dynamics. At the same time, our results likely represent a best-case scenario because growth rates were based on data from well-protected lakes in the Brazilian Amazon, while illegal fishing alters growth rates, dispersal, and site fidelity.

The interconnected lakes in the metapopulation network are crucial for sustaining the Arapaima socio-ecological system in the Juruá region. Arapaima can travel up to 90 km, facilitating dispersal and buffering against local disturbances. Their high site fidelity (~77% return to protected lakes) stabilises local populations, while positive growth rates help offset moderate fishing pressure in unprotected lakes, as protected ones serve as juvenile sources. However, without effective FCM, these mechanisms fail, as shown by the sharp population declines when harvesting exceeds 60%, aligning with findings from other regions[36].

Enhancing ecosystem services (ES) is a primary goal in Protected Areas[5,8]. However, the geography scenario, which focused on lakes at the borders of two regional PAs, proved ineffective for Arapaima conservation, especially when illegal fishing exceeded 30%. These protected lakes had some of the lowest Arapaima populations, indicating that top-down management and land demarcation are insufficient without controlling illegal fishing. Similarly, the scenarios based on network connectivity, prioritising either the most or least connected lakes or those based on lake area, did not outperform the business-as-usual or carrying capacity schemes at the lake or the metapopulation scales.

Despite the benefits of the carrying capacity scheme, it may exacerbate illegal fishing, which is widespread across the Amazon. Market saturation with illegal products drives down prices, fosters unfair competition, and undermines fair trade efforts[30]. While there is potential to expand Arapaima trade to other Brazilian states or for export, current consumption remains concentrated in the Northern region, where the annual harvest easily saturates the market. Increasing Arapaima populations in unprotected areas could further destabilise the market, encouraging unfair practices and weakening the sustainability of managed fisheries.

In many developing countries, small-scale fisheries lack protection frameworks[9]. The successful Arapaima FCM could be expanded to other Amazon regions to enhance biodiversity conservation and local well-being. In the Jarauá channel within the Mamirauá Sustainable Development Reserve, where Arapaima counting methods and FCM began in 1999[37], the recovery of Arapaima populations from near extinction was key in shaping government policies[6]. Current federal legislation, which enforces a 0.3 fishing quota, has ensured fisheries ecosystem services at a regional scale. Expanding similar FCM schemes across the Amazon could further enhance sustainable fishing services. Nevertheless, effective management must address the local conditions underlying the socio-ecological networks in the area applied, aiming beyond minimum standards to optimise spatial, ecological, and social factors influencing species population dynamics[10].

Our study highlights the need for data-driven, context-specific management strategies to sustain the Arapaima fishery, revealing that while the current FCM approach stabilises populations, protecting lakes based on carrying capacity enhances resilience, particularly against illegal fishing pressures. Expanding this and other successful FCM practices across the Amazon could significantly benefit conservation and local well-being. However, models should integrate local knowledge with data and be interpreted with care, given the complexity of social-ecological systems. Ultimately, data-driven selection of optimal strategies to balance ecological sustainability with the needs of local communities is key to the long-term success of FCM and similar conservation strategies.

Methods

Study system

We studied 31 oxbow lakes along the Juruá River Basin, Western Brazilian Amazon, harbouring a set of 13 local fisheries that rely on the sustainable harvest of Arapaima for subsistence and local economy (Fig 1, Table S1). Lakes and fishing communities are part of both a territorial management, which includes two protected areas (PA; Uacari Sustainable Development Reserve and Médio Juruá Extractivism Reserve), and a community-based management (FCM). Lakes within PAs are protected by law, thus illegal fishing is theoretically absent in the lakes within. However, it is clear from local knowledge that PAs are not enough to guarantee a sustainable fishing in the region. In turn, the current FCM scheme at Juruá River works equally well for lakes within and outside PAs[38,39]. Within this FCM scheme, local communities are legally empowered to protect their fishing grounds (most oxbow lakes) against large-scale commercial and illegal fisheries. During the dry season, oxbow lakes are discrete units in the riverscape that can be monopolised by one or a few fishing communities.

Fishing quotas for each community are granted according to the Arapaima population size in each managed lake, which have been monitored for at least three consecutive years before entering the FCM scheme. Fishing quotas are granted by the federal governmental agency (Instituto Brasileiro do Meio Ambiente - IBAMA) in accordance with fishing communities and local associations and can vary over time. The legal fishing quota applies only to lakes within the FCM scheme and can reach up to 30% of the Arapaima population of a given lake. Lakes outside FCM and/or conservation units may experience illegal fishing all year around[30]. For this study, **protected lakes** (13 lakes) correspond to 'no-take' areas designed to ensure the Arapaima reproduction, in which fisheries are not permitted apart from a sustainable off-take during a short period once each year and based on a strict fishing quota; protected lakes are co-managed by local communities that follow IBAMA regulations. In turn **unprotected lakes (18 lakes)** are not managed by FCM nor IBAMA and are prone to exploitation by commercial fisheries that are generally uncontrolled, and all sorts of illegal fisheries.

Dataset

We gathered data on Arapaima population numbers across all studied lakes from a previous study[25] and FCM information from our local partner institution (Juruá Institute, institutojurua.org.br). The Arapaima population dataset contains the number of adults in each lake in 2013, counted by local experts and following methods developed and validated elsewhere[37]. Additionally, we retrieved temporal Arapaima population data from annual reports submitted by the local associations (Associação de Produtores Rurais de Carauari - ASPROC, and Associação de Moradores Extrativistas da Comunidade São Raimundo – AMECSARA) to IBAMA. We compiled a temporal series from 2011-2022 containing the number of Arapaima juveniles and adults in each of the 31 study lakes, also counted by local expert fishers as part of the FCM. Yet, the year that FCM started in each lake was different and 21 of those did not have continuous information. Therefore, only a subset of lakes were used as the baseline for modelling population dynamics (see below).

Metapopulation network

We represented the riverscape formed by a set of Arapaima populations and their spatial connectivity as a weighted directed network in which nodes represent local patches of habitats (i.e. oxbow lakes) and links between them represent dispersal corridors that the species can use to move across the riverscape. Links between lakes were defined quantitatively as a combination of three components of the riverscape: the distance between lakes, the Arapaima's dispersal ability, and its return rate after high-tide migration, as follows:

<u>i. Distance:</u> the pairwise river-flow geographic distance (km) between lakes *i* (source) and *j* (target), d_{ij}, during the flooding season, when the high tides of the Juruá River enable fish movement from lake to lake. Distance was estimated using the 'Base Hidrográfica Ottocodificada (BHO) Multiescalas 2017 5k (BHO 2017 5k), an hydrographic database available from the National Water Agency of Brazil[40]. The hydrographic basin follows the Pfafstetter Coding System that includes topological information within the code, extracted from the Shuttle Radar Topography Mission - SRTM, mapped from 11 to 22 February 2000, with a 30 m spatial resolution. Distances were calculated using the Quantum GIS 3.32[41] software and the analytical extension called QNEAT3. We calculated the river-flow geographic distance among lakes as the sum of distances resulting from: (i) the Euclidian distance from the source lake *i* to the nearest river channel; (ii) the distance from the entry point to the

exit cost towards lake *j* following the river course; and (iii) the Euclidian distance from the exit point to the destination lake j. We scaled d_{ij} to reflect the fact that the closer two lakes are, the stronger their link, and consequently the ability of a fish to reach the target lake. Scaling followed the formula:

$$d'_{ij} = 1/[log(d_{ij})/min(d)] \tag{1}$$

where min(d) is the minimum distance across all pairs of lakes. d'_{ij} ranges between 0 and 1. We then normalised the outgoing links of each lake i by dividing each of them by their sum (analogous to dividing the row of a matrix by its sum), using the formula:

$$v_{ij} = d'_{ij}/\sum_{j=1\neq i} d'_{ij} \qquad (2)$$

This provided the relative probability of fish to move to any lake j from a source lake i. This method is similar to calculating the flow of information in social and ecological networks[42,43].

ii. Dispersal capacity: The maximum distance travelled by an adult Arapaima individual during the high-tide river flooding, which was recorded by GPS tracker as 90 km (Campos-Silva, pers. knowledge). We set the links in which pairwise distances were above 90 km to zero.

iii. Return rate: The average return rate of adult Arapaima individuals to their lake of origin, where they stay during the dry season. Previous studies found that a high proportion of individuals from lakes under FCM return to their lake of departure, ranging from 71% to 83% [28,29]. We used an average return rate (λ) of 0.77 to lakes under the FCM scheme. Lake connectivity was then multiplied by $1 - \lambda$, reflecting the proportion of individuals that will not return to the departure lake, thus effectively contributing to network connectivity.

We integrated three components into a single metric for pairwise connectivity between lakes, which is the weight of a link in the metapopulation network, ω_{ij} , as follows:

$\omega_{ij} = 0$, if distance between a pair of lakes is above 90 km, otherwise,

$\omega_{ij} = v_{ij}$, if lake *k* is not under FCM management, otherwise

$\omega_{ij} = v_{ij}(1 - \lambda)$, if lake *k* is under FCM management (3)

Metapopulation model

To investigate the potential effects of changing fishing policies on Arapaima across the riverscape shown in Fig 1, we considered the set of lakes connected via the metapopulation network described above as a metapopulation composed of local Arapaima populations / habitat patches. We modelled each lake's local population growth using a density-dependent growth equation and dispersal following the established connectivity between lakes (see *Metapopulation network*). We used the Ricker population equation[44], with an added stochastic term to account for the effects of year-to-year environmental variability on population growth, to model local population dynamics:

$$N_{t+1} = N_t e^{r(1-N_t/K)+\varepsilon} \quad (4)$$

where N_t is the abundance of the population at time *t*, *r* is the intrinsic growth rate of the population, and *K* is its carrying capacity. ε is a normally distributed stochastic variable representing stochastic environmental variability in population growth $\varepsilon \sim N(0, \sigma)$.

To leverage the data collected from our study system, we derived empirical values for the model parameters from the temporal abundance data of local Arapaima populations in specific lakes (see the Dataset subsection above). From this dataset, we selected a time series of adult Arapaima population abundance within specific lakes, focusing on those with at least seven consecutive data points (years) available between 2011 and 2022 (see Table S6). This criterion yielded 10 lakes for which population abundances were considered of enough resolution to calculate parameters *r* and *K* for the model above (Eq. 4). The lakes selected were: Branco

(5), Dona Maria (6), Janiceto (9), Manaria (10), Mandioca (11), Marari (12), Onça (14), Sacado do Juburi (19), Samaúma (20) and Santo Antônio (22) (Fig 1).

To calculate *r* and *K*, we conducted a linear regression analysis over the per-capita growth rate, calculated as $ln(N_{t+1}/N_t)$, against N_t for each of these 10 populations independently, with *r* being the y-intercept and *K* the x-intercept, respectively. Using this information, we used a constant value of *r* = 1.04 across all local populations in the model, which was equal to the average value across these ten populations[28]. We additionally calculated σ as the variance of this set of *r* values ($\sigma = 0.085$). Information on carrying capacities for each local population *K* was complemented with local fisher expert knowledge (Campos-Silva, pers. knowledge), and assigned individually to each local population, including those for which semi-complete temporal series were not available. Values of *K* for each local population are shown in Table S6.

We connected local populations growing according to Eq. 4 through dispersal, as defined by the metapopulation network. To do so, we incorporated an influx and outflux terms into the model:

$$N_{t,i} = N_{t-1,i} e^{r(1-N_{t-1,l}/K_i)+\varepsilon} + \sum_{j=1,i\neq j}^{L} \omega_{ij} N_{t,j} - \sum_{j=1,j\neq i}^{L} \omega_{ji} N_{t,i} \tag{5}$$

where $N_{t,i}$ is the abundance of Arapaima population in lake *i* at time *t*, *L* is the total number of lakes, and rates ω_{ij} and ω_{ji} are the dispersal rates from lake *i* to *j* and from lake *j* to *i*, respectively. To incorporate the effects of harvesting into our metapopulation model, we added an extra term for harvesting rate, extending Eq 5 to:

$$N_{t,i} = N_{t-1,i} e^{r(1-N_{t-1,l}/K_i)+\varepsilon} + \sum_{j=1,i\neq j}^{L} \omega_{ij} N_{t,j} - \sum_{j=1,j\neq i}^{L} \omega_{ji} N_{t,i} - hN_{t,i} \tag{6}$$

where *h* is the harvesting rate, or fishing effort (i.e. the fraction of Arapaima fishes extracted from the population). For each of the scenarios (Table 1) we varied *h* across a range of values from 0 to 1 at 0.1 intervals, for unprotected lakes only. This yielded a total of 11 values of harvesting rate. For protected lakes we used 0.3 for values of h > 0.3 to ensure protection.

We ran numerical simulations for each management scenario by starting the metapopulation at random initial abundances across local lakes, chosen from a uniform distribution across the values of *K* (i.e. $N_{1,i} \sim U(min(K), max(K)) \ \forall \ i$). We used a different metapopulation network for each scenario because we varied the protected and unprotected lakes (Table 1). For instance, when choosing to protect larger lakes (H4), we changed the metapopulation network by defining the 13 lakes with the greater area as protected and the 18 remaining ones as unprotected. This was repeated for all scenarios based on the criterion used. For scenario 7 (protected lakes selected randomly) we ran 1000 replicates in which the identity of the 13 protected lakes was drawn randomly and independently for each replicate. This procedure, however, inherently results in lakes being assigned either protected or unprotected status across different replicates (since they are assigned their protection status randomly). To circumvent this, the resulting population abundances and harvested biomass were averaged across replicates of the same lake and protection status.

Then, we applied the protocol described in the ‘Metapopulation model’ section. This was necessary because return rates only apply to protected lakes[28,29] , which indeed change from scenario to scenario (Table S2). We ran simulations for 50 time steps, where the first 10 time steps were run without harvesting. This initial time period was found to be enough for transient dynamics to occur and the system to reach its stochastic equilibrium (i.e., random fluctuations around the lakes’ carrying capacities). At time step 11 harvesting was introduced and maintained for the rest of the simulation (i.e., the further 39 time steps). This time period was enough for the system to reach its new stochastic equilibrium with harvesting. To quantify the simulation outcomes, we calculated lake occupancy (i.e., whether a lake's abundance was greater than 0) and the mean population abundance across the last 10 time steps for each lake.

Statistical analyses

To identify the main determinants of mean population abundance over the last 10 time steps of the model simulations across lakes, we performed a linear regression considering the following fixed effects: (i) scenario, (ii) protection status, (iii) fishing effort, and the pairwise interactions between each of these variables. To account for the non-independence of observations from the same lake, we added lake as a random effect variable to the model. The fitted full model was:

$$log_{10}(mean\ population\ abundance\ +1) \sim scenario + protected + fishing\ effort + scenario :: protected + scenario :: fishing\ effort + protected :: fishing\ effort + (1|lake) \tag{7}$$

We used a model selection framework to compare combinations of those variables to each other and to the full model. We selected the model producing the best fit using the Akaike Information Criteria (AIC). We considered all possible combinations of independent variables in the competing models and retained the model with the lowest AIC. Mixed effect models and the model selection procedure were implemented using the *lmer* function of the *lme4* package[45] and the *dredge* function of the *MuMIn* package[46], respectively. To conduct a more detailed analysis of specific pairwise comparisons across scenarios, protection status, and fishing effort, we computed the Estimated Marginal Means for each combination of interest, applying the Tukey-adjusted test for multiple comparisons implemented in the *emmeans* function at the *emmeans*[47] library. All statistical analyses were performed in R[48].

Code and data availability

All data and code can be found at the GitHub repository https://github.com/carineemer/SEMLN_Jurua.

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Supplementary Material

Demography-based management of a lake meta-population network boosts food security in Amazonian fisheries

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This file contains:

Tables S1-S6.

Figures S1-S4.

Table S1. The studied lakes at the Middle Juruá River Basin, Western Brazilian Amazon, and their respective characteristics. Number of individuals corresponds to the adults of arapaima (*Arapaima gigas*) counted in 2013 by local fisheries. RDS Uacari = Uacari Sustainable Development Reserve; RESEX Médio Juruá = Médio Juruá Extractivism Reserve; FCM = Fisheries Co-Management.

ID	Lake name	Number of individuals	Area (ha)	Out-strength	Latitude	Longitude	FCM	Territorial management
1	Acurau	2	42	0.430	-6.031145	-67.790355	no	RDS Uacari
2	Andreza	3	90	0.190	-5.0981534	-67.140353	no	RESEX Médio Juruá
3	Aruana	10	16	0.349	-5.351325	-67.393483	no	RESEX Médio Juruá
4	Baliera	6	21	0.344	-5.3849685	-67.357977	no	RESEX Médio Juruá
5	Branco	51	15	0.284	-5.1894981	-67.277459	yes	RESEX Médio Juruá
6	Dona Maria	32	101	0.320	-5.4226337	-67.521494	yes	RESEX Médio Juruá
7	Fortuna	20	18.9	0.289	-5.744311	-67.797067	yes	RESEX Médio Juruá
8	Itabaiana	20	28	0.358	-6.004136	-67.769467	no	RDS Uacari
9	Janiceto	2	6	0.316	-5.502431	-67.604511	yes	RESEX Médio Juruá
10	Manaria	4	51.4	0.321	-5.4661852	-67.522265	yes	RESEX Médio Juruá
11	Mandioca	537	293	0.292	-5.8711528	-67.805478	yes	RDS Uacari
12	Marari	259	200	0.332	-5.9410389	-67.76637	yes	RDS Uacari
13	Maximiano	676	269	0.336	-5.7611366	-67.813029	no	RDS Uacari
14	Onça	23	11	0.384	-5.5426804	-67.602305	yes	RESEX Médio Juruá

15	Preto	1	32.7	0.221	-5.1012113	-67.180216	no	RESEX Médio Juruá
16	Recreio	3	25.6	0.323	-5.531497	-67.572317	no	RDS Uacari
17	Redondo	2	82.4	0.284	-5.98159	-67.78053	yes	RDS Uacari
18	Sacado do Erê	6	306	0.171	-5.124628	-66.9676	no	open access
19	Sacado do Juburi	357	412	0.293	-5.1468528	-67.224808	yes	RESEX Médio Juruá
20	Samaúma	100	105	0.287	-5.5276001	-67.634469	yes	RESEX Médio Juruá
21	Santa Clara	4	200	0.334	-5.9664989	-67.829327	yes	RDS Uacari
22	Santo Antônio	2	53	0.398	-5.5525169	-67.559285	yes	RDS Uacari
23	São Sebastião	3	344	0.248	-6.0592234	-67.877531	no	open access
24	Seco	2	83.4	0.168	-5.061967	-67.037806	no	open access
25	Tabuleiro	67	15.8	0.384	-5.525086	-67.677247	no	RESEX Médio Juruá
26	Tangara	8	37	0.320	-5.7533732	-67.733193	no	RDS Uacari
27	Toare	21	9	0.422	-6.0358136	-67.773306	no	RDS Uacari
28	Tocos	1	6	0.383	-5.527658	-67.689747	no	RESEX Médio Juruá
29	Torcate	67	108	0.349	-5.7307683	-67.776216	no	RDS Uacari
30	Vera	2	8.3	0.356	-5.235111	-67.305066	no	RESEX Médio Juruá
31	Viana	2	18.3	0.287	-5.386906	-67.441497	no	RESEX Médio Juruá

Table S2. List of lakes protected in each scenario, as follows: H1 - Business-as-usual; H2 - Protecting most connected lakes; H3 - Protecting least connected lakes; H4 - Protecting larger lakes; H5 - Protecting lakes with higher carrying capacity; H6 - Protecting lakes according to geographic position. For the random scenario (H7), the protected lakes might change at every iteration thus we are not fixing this information here - see Methods for further information about the random scenario. Details of each scenario can be found in Table 1. Prot = lake protected by FCM; unp = unprotected.

lake	H1	H2	H3	H4	H5	H6
Acurau	unp	prot	unp	unp	unp	prot
Andreza	unp	unp	prot	prot	unp	prot
Aruana	unp	prot	unp	unp	unp	unp
Baliera	unp	unp	unp	unp	unp	unp
Branco	prot	unp	prot	unp	prot	prot
Dona Maria	prot	prot	unp	prot	prot	unp
Fortuna	prot	unp	prot	unp	prot	unp
Itabaiana	unp	prot	unp	unp	prot	prot
Janiceto	prot	unp	unp	unp	unp	unp
Manaria	prot	prot	unp	unp	prot	unp
Mandioca	prot	unp	prot	prot	prot	unp
Marari	prot	unp	prot	prot	prot	prot
Maximiano	unp	unp	unp	prot	unp	unp
Onça	prot	prot	unp	unp	prot	unp
Preto	unp	unp	prot	unp	unp	prot
Recreio	unp	prot	unp	unp	unp	unp
Redondo	prot	unp	prot	prot	unp	prot
Sacado do Ere	unp	unp	prot	prot	unp	prot
Sacado do Juburi	prot	unp	prot	prot	prot	prot
Samaúma	prot	unp	unp	prot	prot	unp

Santa Clara	prot	unp	prot	prot	unp	prot
Santo Antônio	prot	prot	unp	unp	unp	unp
São Sebastião	unp	unp	prot	prot	unp	prot
Seco	unp	unp	prot	prot	unp	prot
Tabuleiro	unp	prot	unp	unp	prot	unp
Tangara	unp	unp	prot	unp	unp	unp
Toare	unp	prot	unp	unp	prot	prot
Tocos	unp	prot	unp	unp	unp	unp
Torcate	unp	unp	unp	prot	prot	unp
Vera	unp	prot	unp	unp	unp	unp
Viana	unp	prot	unp	unp	unp	unp

Table S3. Results from the Linear Mixed Model showing the effects of lake protection, management scenarios and different levels of fishing effort, as well as the interactions among them on the population of Arapaima (*Arapaima gigas*) at Middle Juruá River BAsin, Western Amazon. The full model was selected as the best model according to Akaike Information Criteria (LogLik = -420, Delta = 0, AIC = 1); therefore, only the results of this model are shown below. Details of each scenario can be found in Table 1.

Full model: log10(pop.means + 1) ~ scenario + protected + fishing_effort + scenario:protected + protected:exploitation_effort + scenario:fishing_effort + (1 |lake)

	Estimate	**Std. Error**	**df**	**t value**	**Pr(>|t|)**
(Intercept)	1.980	0.081	40.905	24.514	4.5E-26
Fishing effort	-1.385	0.048	2675.972	-28.782	6.1E-159
Protected (intercept =	-0.572	0.036	2679.108	-16.008	3.7E-55
scenario2	-0.233	0.043	2677.098	-5.411	6.8E-08
scenario3	-0.200	0.043	2676.630	-4.680	3.0E-06
scenario4	-0.098	0.043	2676.566	-2.285	2.2E-02
scenario5	0.059	0.043	2676.319	1.382	1.7E-01
scenario6	-0.243	0.043	2676.777	-5.662	1.7E-08
scenario7	-0.325	0.037	2676.485	-8.673	7.1E-18
Fishing effort:Protected	1.368	0.033	2675.972	41.553	1.2E-291
Fishing effort:scenario2	-0.430	0.065	2675.972	-6.588	5.4E-11
Fishing effort:scenario3	-0.283	0.065	2675.972	-4.333	1.5E-05
Fishing effort:scenario4	-0.090	0.065	2675.972	-1.375	1.7E-01
Fishing effort:scenario5	0.028	0.065	2675.972	0.436	6.6E-01
Fishing effort:scenario6	-0.335	0.065	2675.972	-5.136	3.0E-07
Fishing effort:scenario7	-0.267	0.057	2675.972	-4.718	2.5E-06
Protected:scenario2	0.257	0.046	2681.441	5.624	2.1E-08
Protected:scenario3	0.211	0.044	2679.391	4.761	2.0E-06
Protected:scenario4	0.062	0.044	2679.082	1.400	1.6E-01
Protected:scenario5	-0.017	0.043	2677.864	-0.402	6.9E-01

Protected:scenario6	0.249	0.045	2680.035	5.539	3.3E-08
Protected:scenario7	0.287	0.038	2678.778	7.594	4.3E-14

Table S4. Post-hoc Tukey test of the Estimated Average Means (EMMeans) of arapaima population in protected and unprotected lakes in each Fishery CoManagement (FCM) scenario, following the Linear Mixed Effect Model. Only comparisons between unprotected and protected lakes within each scenario are shown. Unprotected = lakes not protected by FCM; Protected = lakes protected by FCM. Numbers 1 to 7 correspond to each scenario, as follows: 1 - Business-as-usual; 2 - Protecting most connected lakes; 3 - Protecting least connected lakes; 4 - Protecting larger lakes; 5 - Protecting lakes with higher carrying capacity; 6 - Protecting lakes according to geographic position; 7 - Protecting lakes randomly. Details of each scenario can be found in Table 1.

contrast	scenario	estimate	SE	df	t.ratio	p.value
Unprotected - Protected	1	-0.112	0.032	2679.950	-3.545	0.000
Unprotected - Protected	2	-0.370	0.032	2680.938	-11.564	0.000
Unprotected - Protected	3	-0.323	0.032	2681.099	-10.097	0.000
Unprotected - Protected	4	-0.174	0.032	2680.590	-5.467	0.000
Unprotected - Protected	5	-0.095	0.032	2679.794	-3.000	0.003
Unprotected - Protected	6	-0.361	0.032	2680.373	-11.365	0.000
Unprotected - Protected	7	-0.399	0.021	2676.000	-19.375	0.000

Table S5. Post-hoc Tukey test for the Estimated Marginal Means (EMMeans) of Arapaima population, showing pairwise differences between fishing effort in each scenario. Numbers 1 to 7 correspond to each scenario, as follows: 1 - Business-as-usual; 2 - Protecting most connected lakes; 3 - Protecting least connected lakes; 4 - Protecting larger lakes; 5 - Protecting lakes with higher carrying capacity; 6 - Protecting lakes according to geographic position; 7 - Protecting lakes randomly. Details of each scenario can be found in Table 1.

contrast	scenario	estimate	SE	df	t.ratio
Fishing effort 0 - Fishing effort 0.1	1	0.070	0.005	2676.000	15.183
Fishing effort 0 - Fishing effort 0.2	1	0.140	0.009	2676.000	15.183
Fishing effort 0 - Fishing effort 0.3	1	0.210	0.014	2676.000	15.183
Fishing effort 0 - Fishing effort 0.4	1	0.280	0.018	2676.000	15.183
Fishing effort 0 - Fishing effort 0.5	1	0.351	0.023	2676.000	15.183
Fishing effort 0 - Fishing effort 0.6	1	0.421	0.028	2676.000	15.183
Fishing effort 0 - Fishing effort 0.7	1	0.491	0.032	2676.000	15.183
Fishing effort 0 - Fishing effort 0.8	1	0.561	0.037	2676.000	15.183
Fishing effort 0 - Fishing effort 0.9	1	0.631	0.042	2676.000	15.183
Fishing effort 0 - Fishing effort 1	1	0.701	0.046	2676.000	15.183
Fishing effort 0.1 - Fishing effort 0.2	1	0.070	0.005	2676.000	15.183
Fishing effort 0.1 - Fishing effort 0.3	1	0.140	0.009	2676.000	15.183
Fishing effort 0.1 - Fishing effort 0.4	1	0.210	0.014	2676.000	15.183
Fishing effort 0.1 - Fishing effort 0.5	1	0.280	0.018	2676.000	15.183
Fishing effort 0.1 - Fishing effort 0.6	1	0.351	0.023	2676.000	15.183
Fishing effort 0.1 - Fishing effort 0.7	1	0.421	0.028	2676.000	15.183

Fishing effort 0.1 - Fishing effort 0.8	1	0.491	0.032	2676.000	15.183
Fishing effort 0.1 - Fishing effort 0.9	1	0.561	0.037	2676.000	15.183
Fishing effort 0.1 - Fishing effort 1	1	0.631	0.042	2676.000	15.183
Fishing effort 0.2 - Fishing effort 0.3	1	0.070	0.005	2676.000	15.183
Fishing effort 0.2 - Fishing effort 0.4	1	0.140	0.009	2676.000	15.183
Fishing effort 0.2 - Fishing effort 0.5	1	0.210	0.014	2676.000	15.183
Fishing effort 0.2 - Fishing effort 0.6	1	0.280	0.018	2676.000	15.183
Fishing effort 0.2 - Fishing effort 0.7	1	0.351	0.023	2676.000	15.183
Fishing effort 0.2 - Fishing effort 0.8	1	0.421	0.028	2676.000	15.183
Fishing effort 0.2 - Fishing effort 0.9	1	0.491	0.032	2676.000	15.183
Fishing effort 0.2 - Fishing effort 1	1	0.561	0.037	2676.000	15.183
Fishing effort 0.3 - Fishing effort 0.4	1	0.070	0.005	2676.000	15.183
Fishing effort 0.3 - Fishing effort 0.5	1	0.140	0.009	2676.000	15.183
Fishing effort 0.3 - Fishing effort 0.6	1	0.210	0.014	2676.000	15.183
Fishing effort 0.3 - Fishing effort 0.7	1	0.280	0.018	2676.000	15.183
Fishing effort 0.3 - Fishing effort 0.8	1	0.351	0.023	2676.000	15.183
Fishing effort 0.3 - Fishing effort 0.9	1	0.421	0.028	2676.000	15.183
Fishing effort 0.3 - Fishing effort 1	1	0.491	0.032	2676.000	15.183
Fishing effort 0.4 - Fishing effort 0.5	1	0.070	0.005	2676.000	15.183
Fishing effort 0.4 - Fishing effort 0.6	1	0.140	0.009	2676.000	15.183

Fishing effort 0.4 - Fishing effort 0.7	1	0.210	0.014	2676.000	15.183
Fishing effort 0.4 - Fishing effort 0.8	1	0.280	0.018	2676.000	15.183
Fishing effort 0.4 - Fishing effort 0.9	1	0.351	0.023	2676.000	15.183
Fishing effort 0.4 - Fishing effort 1	1	0.421	0.028	2676.000	15.183
Fishing effort 0.5 - Fishing effort 0.6	1	0.070	0.005	2676.000	15.183
Fishing effort 0.5 - Fishing effort 0.7	1	0.140	0.009	2676.000	15.183
Fishing effort 0.5 - Fishing effort 0.8	1	0.210	0.014	2676.000	15.183
Fishing effort 0.5 - Fishing effort 0.9	1	0.280	0.018	2676.000	15.183
Fishing effort 0.5 - Fishing effort 1	1	0.351	0.023	2676.000	15.183
Fishing effort 0.6 - Fishing effort 0.7	1	0.070	0.005	2676.000	15.183
Fishing effort 0.6 - Fishing effort 0.8	1	0.140	0.009	2676.000	15.183
Fishing effort 0.6 - Fishing effort 0.9	1	0.210	0.014	2676.000	15.183
Fishing effort 0.6 - Fishing effort 1	1	0.280	0.018	2676.000	15.183
Fishing effort 0.7 - Fishing effort 0.8	1	0.070	0.005	2676.000	15.183
Fishing effort 0.7 - Fishing effort 0.9	1	0.140	0.009	2676.000	15.183
Fishing effort 0.7 - Fishing effort 1	1	0.210	0.014	2676.000	15.183
Fishing effort 0.8 - Fishing effort 0.9	1	0.070	0.005	2676.000	15.183
Fishing effort 0.8 - Fishing effort 1	1	0.140	0.009	2676.000	15.183
Fishing effort 0.9 - Fishing effort 1	1	0.070	0.005	2676.000	15.183
Fishing effort 0 - Fishing effort 0.1	2	0.113	0.005	2676.000	24.484

Fishing effort 0 - Fishing effort 0.2	2	0.226	0.009	2676.000	24.484
Fishing effort 0 - Fishing effort 0.3	2	0.339	0.014	2676.000	24.484
Fishing effort 0 - Fishing effort 0.4	2	0.452	0.018	2676.000	24.484
Fishing effort 0 - Fishing effort 0.5	2	0.565	0.023	2676.000	24.484
Fishing effort 0 - Fishing effort 0.6	2	0.678	0.028	2676.000	24.484
Fishing effort 0 - Fishing effort 0.7	2	0.791	0.032	2676.000	24.484
Fishing effort 0 - Fishing effort 0.8	2	0.905	0.037	2676.000	24.484
Fishing effort 0 - Fishing effort 0.9	2	1.018	0.042	2676.000	24.484
Fishing effort 0 - Fishing effort 1	2	1.131	0.046	2676.000	24.484
Fishing effort 0.1 - Fishing effort 0.2	2	0.113	0.005	2676.000	24.484
Fishing effort 0.1 - Fishing effort 0.3	2	0.226	0.009	2676.000	24.484
Fishing effort 0.1 - Fishing effort 0.4	2	0.339	0.014	2676.000	24.484
Fishing effort 0.1 - Fishing effort 0.5	2	0.452	0.018	2676.000	24.484
Fishing effort 0.1 - Fishing effort 0.6	2	0.565	0.023	2676.000	24.484
Fishing effort 0.1 - Fishing effort 0.7	2	0.678	0.028	2676.000	24.484
Fishing effort 0.1 - Fishing effort 0.8	2	0.791	0.032	2676.000	24.484
Fishing effort 0.1 - Fishing effort 0.9	2	0.905	0.037	2676.000	24.484
Fishing effort 0.1 - Fishing effort 1	2	1.018	0.042	2676.000	24.484
Fishing effort 0.2 - Fishing effort 0.3	2	0.113	0.005	2676.000	24.484
Fishing effort 0.2 - Fishing effort 0.4	2	0.226	0.009	2676.000	24.484

Fishing effort 0.2 - Fishing effort 0.5	2	0.339	0.014	2676.000	24.484
Fishing effort 0.2 - Fishing effort 0.6	2	0.452	0.018	2676.000	24.484
Fishing effort 0.2 - Fishing effort 0.7	2	0.565	0.023	2676.000	24.484
Fishing effort 0.2 - Fishing effort 0.8	2	0.678	0.028	2676.000	24.484
Fishing effort 0.2 - Fishing effort 0.9	2	0.791	0.032	2676.000	24.484
Fishing effort 0.2 - Fishing effort 1	2	0.905	0.037	2676.000	24.484
Fishing effort 0.3 - Fishing effort 0.4	2	0.113	0.005	2676.000	24.484
Fishing effort 0.3 - Fishing effort 0.5	2	0.226	0.009	2676.000	24.484
Fishing effort 0.3 - Fishing effort 0.6	2	0.339	0.014	2676.000	24.484
Fishing effort 0.3 - Fishing effort 0.7	2	0.452	0.018	2676.000	24.484
Fishing effort 0.3 - Fishing effort 0.8	2	0.565	0.023	2676.000	24.484
Fishing effort 0.3 - Fishing effort 0.9	2	0.678	0.028	2676.000	24.484
Fishing effort 0.3 - Fishing effort 1	2	0.791	0.032	2676.000	24.484
Fishing effort 0.4 - Fishing effort 0.5	2	0.113	0.005	2676.000	24.484
Fishing effort 0.4 - Fishing effort 0.6	2	0.226	0.009	2676.000	24.484
Fishing effort 0.4 - Fishing effort 0.7	2	0.339	0.014	2676.000	24.484
Fishing effort 0.4 - Fishing effort 0.8	2	0.452	0.018	2676.000	24.484
Fishing effort 0.4 - Fishing effort 0.9	2	0.565	0.023	2676.000	24.484
Fishing effort 0.4 - Fishing effort 1	2	0.678	0.028	2676.000	24.484
Fishing effort 0.5 - Fishing effort 0.6	2	0.113	0.005	2676.000	24.484

Fishing effort 0.5 - Fishing effort 0.7	2	0.226	0.009	2676.000	24.484
Fishing effort 0.5 - Fishing effort 0.8	2	0.339	0.014	2676.000	24.484
Fishing effort 0.5 - Fishing effort 0.9	2	0.452	0.018	2676.000	24.484
Fishing effort 0.5 - Fishing effort 1	2	0.565	0.023	2676.000	24.484
Fishing effort 0.6 - Fishing effort 0.7	2	0.113	0.005	2676.000	24.484
Fishing effort 0.6 - Fishing effort 0.8	2	0.226	0.009	2676.000	24.484
Fishing effort 0.6 - Fishing effort 0.9	2	0.339	0.014	2676.000	24.484
Fishing effort 0.6 - Fishing effort 1	2	0.452	0.018	2676.000	24.484
Fishing effort 0.7 - Fishing effort 0.8	2	0.113	0.005	2676.000	24.484
Fishing effort 0.7 - Fishing effort 0.9	2	0.226	0.009	2676.000	24.484
Fishing effort 0.7 - Fishing effort 1	2	0.339	0.014	2676.000	24.484
Fishing effort 0.8 - Fishing effort 0.9	2	0.113	0.005	2676.000	24.484
Fishing effort 0.8 - Fishing effort 1	2	0.226	0.009	2676.000	24.484
Fishing effort 0.9 - Fishing effort 1	2	0.113	0.005	2676.000	24.484
Fishing effort 0 - Fishing effort 0.1	3	0.098	0.005	2676.000	21.301
Fishing effort 0 - Fishing effort 0.2	3	0.197	0.009	2676.000	21.301
Fishing effort 0 - Fishing effort 0.3	3	0.295	0.014	2676.000	21.301
Fishing effort 0 - Fishing effort 0.4	3	0.393	0.018	2676.000	21.301
Fishing effort 0 - Fishing effort 0.5	3	0.492	0.023	2676.000	21.301
Fishing effort 0 - Fishing effort 0.6	3	0.590	0.028	2676.000	21.301

Fishing effort 0 - Fishing effort 0.7	3	0.689	0.032	2676.000	21.301
Fishing effort 0 - Fishing effort 0.8	3	0.787	0.037	2676.000	21.301
Fishing effort 0 - Fishing effort 0.9	3	0.885	0.042	2676.000	21.301
Fishing effort 0 - Fishing effort 1	3	0.984	0.046	2676.000	21.301
Fishing effort 0.1 - Fishing effort 0.2	3	0.098	0.005	2676.000	21.301
Fishing effort 0.1 - Fishing effort 0.3	3	0.197	0.009	2676.000	21.301
Fishing effort 0.1 - Fishing effort 0.4	3	0.295	0.014	2676.000	21.301
Fishing effort 0.1 - Fishing effort 0.5	3	0.393	0.018	2676.000	21.301
Fishing effort 0.1 - Fishing effort 0.6	3	0.492	0.023	2676.000	21.301
Fishing effort 0.1 - Fishing effort 0.7	3	0.590	0.028	2676.000	21.301
Fishing effort 0.1 - Fishing effort 0.8	3	0.689	0.032	2676.000	21.301
Fishing effort 0.1 - Fishing effort 0.9	3	0.787	0.037	2676.000	21.301
Fishing effort 0.1 - Fishing effort 1	3	0.885	0.042	2676.000	21.301
Fishing effort 0.2 - Fishing effort 0.3	3	0.098	0.005	2676.000	21.301
Fishing effort 0.2 - Fishing effort 0.4	3	0.197	0.009	2676.000	21.301
Fishing effort 0.2 - Fishing effort 0.5	3	0.295	0.014	2676.000	21.301
Fishing effort 0.2 - Fishing effort 0.6	3	0.393	0.018	2676.000	21.301
Fishing effort 0.2 - Fishing effort 0.7	3	0.492	0.023	2676.000	21.301
Fishing effort 0.2 - Fishing effort 0.8	3	0.590	0.028	2676.000	21.301
Fishing effort 0.2 - Fishing effort 0.9	3	0.689	0.032	2676.000	21.301

Fishing effort 0.2 - Fishing effort 1	3	0.787	0.037	2676.000	21.301
Fishing effort 0.3 - Fishing effort 0.4	3	0.098	0.005	2676.000	21.301
Fishing effort 0.3 - Fishing effort 0.5	3	0.197	0.009	2676.000	21.301
Fishing effort 0.3 - Fishing effort 0.6	3	0.295	0.014	2676.000	21.301
Fishing effort 0.3 - Fishing effort 0.7	3	0.393	0.018	2676.000	21.301
Fishing effort 0.3 - Fishing effort 0.8	3	0.492	0.023	2676.000	21.301
Fishing effort 0.3 - Fishing effort 0.9	3	0.590	0.028	2676.000	21.301
Fishing effort 0.3 - Fishing effort 1	3	0.689	0.032	2676.000	21.301
Fishing effort 0.4 - Fishing effort 0.5	3	0.098	0.005	2676.000	21.301
Fishing effort 0.4 - Fishing effort 0.6	3	0.197	0.009	2676.000	21.301
Fishing effort 0.4 - Fishing effort 0.7	3	0.295	0.014	2676.000	21.301
Fishing effort 0.4 - Fishing effort 0.8	3	0.393	0.018	2676.000	21.301
Fishing effort 0.4 - Fishing effort 0.9	3	0.492	0.023	2676.000	21.301
Fishing effort 0.4 - Fishing effort 1	3	0.590	0.028	2676.000	21.301
Fishing effort 0.5 - Fishing effort 0.6	3	0.098	0.005	2676.000	21.301
Fishing effort 0.5 - Fishing effort 0.7	3	0.197	0.009	2676.000	21.301
Fishing effort 0.5 - Fishing effort 0.8	3	0.295	0.014	2676.000	21.301
Fishing effort 0.5 - Fishing effort 0.9	3	0.393	0.018	2676.000	21.301
Fishing effort 0.5 - Fishing effort 1	3	0.492	0.023	2676.000	21.301
Fishing effort 0.6 - Fishing effort 0.7	3	0.098	0.005	2676.000	21.301

Fishing effort 0.6 - Fishing effort 0.8	3	0.197	0.009	2676.000	21.301
Fishing effort 0.6 - Fishing effort 0.9	3	0.295	0.014	2676.000	21.301
Fishing effort 0.6 - Fishing effort 1	3	0.393	0.018	2676.000	21.301
Fishing effort 0.7 - Fishing effort 0.8	3	0.098	0.005	2676.000	21.301
Fishing effort 0.7 - Fishing effort 0.9	3	0.197	0.009	2676.000	21.301
Fishing effort 0.7 - Fishing effort 1	3	0.295	0.014	2676.000	21.301
Fishing effort 0.8 - Fishing effort 0.9	3	0.098	0.005	2676.000	21.301
Fishing effort 0.8 - Fishing effort 1	3	0.197	0.009	2676.000	21.301
Fishing effort 0.9 - Fishing effort 1	3	0.098	0.005	2676.000	21.301
Fishing effort 0 - Fishing effort 0.1	4	0.079	0.005	2676.000	17.124
Fishing effort 0 - Fishing effort 0.2	4	0.158	0.009	2676.000	17.124
Fishing effort 0 - Fishing effort 0.3	4	0.237	0.014	2676.000	17.124
Fishing effort 0 - Fishing effort 0.4	4	0.316	0.018	2676.000	17.124
Fishing effort 0 - Fishing effort 0.5	4	0.395	0.023	2676.000	17.124
Fishing effort 0 - Fishing effort 0.6	4	0.474	0.028	2676.000	17.124
Fishing effort 0 - Fishing effort 0.7	4	0.554	0.032	2676.000	17.124
Fishing effort 0 - Fishing effort 0.8	4	0.633	0.037	2676.000	17.124
Fishing effort 0 - Fishing effort 0.9	4	0.712	0.042	2676.000	17.124
Fishing effort 0 - Fishing effort 1	4	0.791	0.046	2676.000	17.124
Fishing effort 0.1 - Fishing effort 0.2	4	0.079	0.005	2676.000	17.124

Fishing effort 0.1 - Fishing effort 0.3	4	0.158	0.009	2676.000	17.124
Fishing effort 0.1 - Fishing effort 0.4	4	0.237	0.014	2676.000	17.124
Fishing effort 0.1 - Fishing effort 0.5	4	0.316	0.018	2676.000	17.124
Fishing effort 0.1 - Fishing effort 0.6	4	0.395	0.023	2676.000	17.124
Fishing effort 0.1 - Fishing effort 0.7	4	0.474	0.028	2676.000	17.124
Fishing effort 0.1 - Fishing effort 0.8	4	0.554	0.032	2676.000	17.124
Fishing effort 0.1 - Fishing effort 0.9	4	0.633	0.037	2676.000	17.124
Fishing effort 0.1 - Fishing effort 1	4	0.712	0.042	2676.000	17.124
Fishing effort 0.2 - Fishing effort 0.3	4	0.079	0.005	2676.000	17.124
Fishing effort 0.2 - Fishing effort 0.4	4	0.158	0.009	2676.000	17.124
Fishing effort 0.2 - Fishing effort 0.5	4	0.237	0.014	2676.000	17.124
Fishing effort 0.2 - Fishing effort 0.6	4	0.316	0.018	2676.000	17.124
Fishing effort 0.2 - Fishing effort 0.7	4	0.395	0.023	2676.000	17.124
Fishing effort 0.2 - Fishing effort 0.8	4	0.474	0.028	2676.000	17.124
Fishing effort 0.2 - Fishing effort 0.9	4	0.554	0.032	2676.000	17.124
Fishing effort 0.2 - Fishing effort 1	4	0.633	0.037	2676.000	17.124
Fishing effort 0.3 - Fishing effort 0.4	4	0.079	0.005	2676.000	17.124
Fishing effort 0.3 - Fishing effort 0.5	4	0.158	0.009	2676.000	17.124
Fishing effort 0.3 - Fishing effort 0.6	4	0.237	0.014	2676.000	17.124
Fishing effort 0.3 - Fishing effort 0.7	4	0.316	0.018	2676.000	17.124

Fishing effort 0.3 - Fishing effort 0.8	4	0.395	0.023	2676.000	17.124
Fishing effort 0.3 - Fishing effort 0.9	4	0.474	0.028	2676.000	17.124
Fishing effort 0.3 - Fishing effort 1	4	0.554	0.032	2676.000	17.124
Fishing effort 0.4 - Fishing effort 0.5	4	0.079	0.005	2676.000	17.124
Fishing effort 0.4 - Fishing effort 0.6	4	0.158	0.009	2676.000	17.124
Fishing effort 0.4 - Fishing effort 0.7	4	0.237	0.014	2676.000	17.124
Fishing effort 0.4 - Fishing effort 0.8	4	0.316	0.018	2676.000	17.124
Fishing effort 0.4 - Fishing effort 0.9	4	0.395	0.023	2676.000	17.124
Fishing effort 0.4 - Fishing effort 1	4	0.474	0.028	2676.000	17.124
Fishing effort 0.5 - Fishing effort 0.6	4	0.079	0.005	2676.000	17.124
Fishing effort 0.5 - Fishing effort 0.7	4	0.158	0.009	2676.000	17.124
Fishing effort 0.5 - Fishing effort 0.8	4	0.237	0.014	2676.000	17.124
Fishing effort 0.5 - Fishing effort 0.9	4	0.316	0.018	2676.000	17.124
Fishing effort 0.5 - Fishing effort 1	4	0.395	0.023	2676.000	17.124
Fishing effort 0.6 - Fishing effort 0.7	4	0.079	0.005	2676.000	17.124
Fishing effort 0.6 - Fishing effort 0.8	4	0.158	0.009	2676.000	17.124
Fishing effort 0.6 - Fishing effort 0.9	4	0.237	0.014	2676.000	17.124
Fishing effort 0.6 - Fishing effort 1	4	0.316	0.018	2676.000	17.124
Fishing effort 0.7 - Fishing effort 0.8	4	0.079	0.005	2676.000	17.124
Fishing effort 0.7 - Fishing effort 0.9	4	0.158	0.009	2676.000	17.124

Fishing effort 0.7 - Fishing effort 1	4	0.237	0.014	2676.000	17.124
Fishing effort 0.8 - Fishing effort 0.9	4	0.079	0.005	2676.000	17.124
Fishing effort 0.8 - Fishing effort 1	4	0.158	0.009	2676.000	17.124
Fishing effort 0.9 - Fishing effort 1	4	0.079	0.005	2676.000	17.124
Fishing effort 0 - Fishing effort 0.1	5	0.067	0.005	2676.000	14.568
Fishing effort 0 - Fishing effort 0.2	5	0.135	0.009	2676.000	14.568
Fishing effort 0 - Fishing effort 0.3	5	0.202	0.014	2676.000	14.568
Fishing effort 0 - Fishing effort 0.4	5	0.269	0.018	2676.000	14.568
Fishing effort 0 - Fishing effort 0.5	5	0.336	0.023	2676.000	14.568
Fishing effort 0 - Fishing effort 0.6	5	0.404	0.028	2676.000	14.568
Fishing effort 0 - Fishing effort 0.7	5	0.471	0.032	2676.000	14.568
Fishing effort 0 - Fishing effort 0.8	5	0.538	0.037	2676.000	14.568
Fishing effort 0 - Fishing effort 0.9	5	0.605	0.042	2676.000	14.568
Fishing effort 0 - Fishing effort 1	5	0.673	0.046	2676.000	14.568
Fishing effort 0.1 - Fishing effort 0.2	5	0.067	0.005	2676.000	14.568
Fishing effort 0.1 - Fishing effort 0.3	5	0.135	0.009	2676.000	14.568
Fishing effort 0.1 - Fishing effort 0.4	5	0.202	0.014	2676.000	14.568
Fishing effort 0.1 - Fishing effort 0.5	5	0.269	0.018	2676.000	14.568
Fishing effort 0.1 - Fishing effort 0.6	5	0.336	0.023	2676.000	14.568
Fishing effort 0.1 - Fishing effort 0.7	5	0.404	0.028	2676.000	14.568

Fishing effort 0.1 - Fishing effort 0.8	5	0.471	0.032	2676.000	14.568
Fishing effort 0.1 - Fishing effort 0.9	5	0.538	0.037	2676.000	14.568
Fishing effort 0.1 - Fishing effort 1	5	0.605	0.042	2676.000	14.568
Fishing effort 0.2 - Fishing effort 0.3	5	0.067	0.005	2676.000	14.568
Fishing effort 0.2 - Fishing effort 0.4	5	0.135	0.009	2676.000	14.568
Fishing effort 0.2 - Fishing effort 0.5	5	0.202	0.014	2676.000	14.568
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Fishing effort 0.4 - Fishing effort 0.9	5	0.336	0.023	2676.000	14.568
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Fishing effort 0.5 - Fishing effort 0.7	5	0.135	0.009	2676.000	14.568
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Fishing effort 0.7 - Fishing effort 0.9	5	0.135	0.009	2676.000	14.568
Fishing effort 0.7 - Fishing effort 1	5	0.202	0.014	2676.000	14.568
Fishing effort 0.8 - Fishing effort 0.9	5	0.067	0.005	2676.000	14.568
Fishing effort 0.8 - Fishing effort 1	5	0.135	0.009	2676.000	14.568
Fishing effort 0.9 - Fishing effort 1	5	0.067	0.005	2676.000	14.568
Fishing effort 0 - Fishing effort 0.1	6	0.104	0.005	2676.000	22.435

Fishing effort 0 - Fishing effort 0.2	6	0.207	0.009	2676.000	22.435
Fishing effort 0 - Fishing effort 0.3	6	0.311	0.014	2676.000	22.435
Fishing effort 0 - Fishing effort 0.4	6	0.414	0.018	2676.000	22.435
Fishing effort 0 - Fishing effort 0.5	6	0.518	0.023	2676.000	22.435
Fishing effort 0 - Fishing effort 0.6	6	0.622	0.028	2676.000	22.435
Fishing effort 0 - Fishing effort 0.7	6	0.725	0.032	2676.000	22.435
Fishing effort 0 - Fishing effort 0.8	6	0.829	0.037	2676.000	22.435
Fishing effort 0 - Fishing effort 0.9	6	0.932	0.042	2676.000	22.435
Fishing effort 0 - Fishing effort 1	6	1.036	0.046	2676.000	22.435
Fishing effort 0.1 - Fishing effort 0.2	6	0.104	0.005	2676.000	22.435
Fishing effort 0.1 - Fishing effort 0.3	6	0.207	0.009	2676.000	22.435
Fishing effort 0.1 - Fishing effort 0.4	6	0.311	0.014	2676.000	22.435
Fishing effort 0.1 - Fishing effort 0.5	6	0.414	0.018	2676.000	22.435
Fishing effort 0.1 - Fishing effort 0.6	6	0.518	0.023	2676.000	22.435
Fishing effort 0.1 - Fishing effort 0.7	6	0.622	0.028	2676.000	22.435
Fishing effort 0.1 - Fishing effort 0.8	6	0.725	0.032	2676.000	22.435
Fishing effort 0.1 - Fishing effort 0.9	6	0.829	0.037	2676.000	22.435
Fishing effort 0.1 - Fishing effort 1	6	0.932	0.042	2676.000	22.435
Fishing effort 0.2 - Fishing effort 0.3	6	0.104	0.005	2676.000	22.435
Fishing effort 0.2 - Fishing effort 0.4	6	0.207	0.009	2676.000	22.435

Fishing effort 0.2 - Fishing effort 0.5	6	0.311	0.014	2676.000	22.435
Fishing effort 0.2 - Fishing effort 0.6	6	0.414	0.018	2676.000	22.435
Fishing effort 0.2 - Fishing effort 0.7	6	0.518	0.023	2676.000	22.435
Fishing effort 0.2 - Fishing effort 0.8	6	0.622	0.028	2676.000	22.435
Fishing effort 0.2 - Fishing effort 0.9	6	0.725	0.032	2676.000	22.435
Fishing effort 0.2 - Fishing effort 1	6	0.829	0.037	2676.000	22.435
Fishing effort 0.3 - Fishing effort 0.4	6	0.104	0.005	2676.000	22.435
Fishing effort 0.3 - Fishing effort 0.5	6	0.207	0.009	2676.000	22.435
Fishing effort 0.3 - Fishing effort 0.6	6	0.311	0.014	2676.000	22.435
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Fishing effort 0.3 - Fishing effort 0.8	6	0.518	0.023	2676.000	22.435
Fishing effort 0.3 - Fishing effort 0.9	6	0.622	0.028	2676.000	22.435
Fishing effort 0.3 - Fishing effort 1	6	0.725	0.032	2676.000	22.435
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Fishing effort 0.4 - Fishing effort 0.6	6	0.207	0.009	2676.000	22.435
Fishing effort 0.4 - Fishing effort 0.7	6	0.311	0.014	2676.000	22.435
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Fishing effort 0.5 - Fishing effort 0.9	6	0.414	0.018	2676.000	22.435
Fishing effort 0.5 - Fishing effort 1	6	0.518	0.023	2676.000	22.435
Fishing effort 0.6 - Fishing effort 0.7	6	0.104	0.005	2676.000	22.435
Fishing effort 0.6 - Fishing effort 0.8	6	0.207	0.009	2676.000	22.435
Fishing effort 0.6 - Fishing effort 0.9	6	0.311	0.014	2676.000	22.435
Fishing effort 0.6 - Fishing effort 1	6	0.414	0.018	2676.000	22.435
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Fishing effort 0.7 - Fishing effort 1	6	0.311	0.014	2676.000	22.435
Fishing effort 0.8 - Fishing effort 0.9	6	0.104	0.005	2676.000	22.435
Fishing effort 0.8 - Fishing effort 1	6	0.207	0.009	2676.000	22.435
Fishing effort 0.9 - Fishing effort 1	6	0.104	0.005	2676.000	22.435
Fishing effort 0 - Fishing effort 0.1	7	0.097	0.003	2676.000	29.689
Fishing effort 0 - Fishing effort 0.2	7	0.194	0.007	2676.000	29.689
Fishing effort 0 - Fishing effort 0.3	7	0.290	0.010	2676.000	29.689
Fishing effort 0 - Fishing effort 0.4	7	0.387	0.013	2676.000	29.689
Fishing effort 0 - Fishing effort 0.5	7	0.484	0.016	2676.000	29.689
Fishing effort 0 - Fishing effort 0.6	7	0.581	0.020	2676.000	29.689

Fishing effort 0 - Fishing effort 0.7	7	0.678	0.023	2676.000	29.689
Fishing effort 0 - Fishing effort 0.8	7	0.774	0.026	2676.000	29.689
Fishing effort 0 - Fishing effort 0.9	7	0.871	0.029	2676.000	29.689
Fishing effort 0 - Fishing effort 1	7	0.968	0.033	2676.000	29.689
Fishing effort 0.1 - Fishing effort 0.2	7	0.097	0.003	2676.000	29.689
Fishing effort 0.1 - Fishing effort 0.3	7	0.194	0.007	2676.000	29.689
Fishing effort 0.1 - Fishing effort 0.4	7	0.290	0.010	2676.000	29.689
Fishing effort 0.1 - Fishing effort 0.5	7	0.387	0.013	2676.000	29.689
Fishing effort 0.1 - Fishing effort 0.6	7	0.484	0.016	2676.000	29.689
Fishing effort 0.1 - Fishing effort 0.7	7	0.581	0.020	2676.000	29.689
Fishing effort 0.1 - Fishing effort 0.8	7	0.678	0.023	2676.000	29.689
Fishing effort 0.1 - Fishing effort 0.9	7	0.774	0.026	2676.000	29.689
Fishing effort 0.1 - Fishing effort 1	7	0.871	0.029	2676.000	29.689
Fishing effort 0.2 - Fishing effort 0.3	7	0.097	0.003	2676.000	29.689
Fishing effort 0.2 - Fishing effort 0.4	7	0.194	0.007	2676.000	29.689
Fishing effort 0.2 - Fishing effort 0.5	7	0.290	0.010	2676.000	29.689
Fishing effort 0.2 - Fishing effort 0.6	7	0.387	0.013	2676.000	29.689
Fishing effort 0.2 - Fishing effort 0.7	7	0.484	0.016	2676.000	29.689
Fishing effort 0.2 - Fishing effort 0.8	7	0.581	0.020	2676.000	29.689
Fishing effort 0.2 - Fishing effort 0.9	7	0.678	0.023	2676.000	29.689

Fishing effort 0.2 - Fishing effort 1	7	0.774	0.026	2676.000	29.689
Fishing effort 0.3 - Fishing effort 0.4	7	0.097	0.003	2676.000	29.689
Fishing effort 0.3 - Fishing effort 0.5	7	0.194	0.007	2676.000	29.689
Fishing effort 0.3 - Fishing effort 0.6	7	0.290	0.010	2676.000	29.689
Fishing effort 0.3 - Fishing effort 0.7	7	0.387	0.013	2676.000	29.689
Fishing effort 0.3 - Fishing effort 0.8	7	0.484	0.016	2676.000	29.689
Fishing effort 0.3 - Fishing effort 0.9	7	0.581	0.020	2676.000	29.689
Fishing effort 0.3 - Fishing effort 1	7	0.678	0.023	2676.000	29.689
Fishing effort 0.4 - Fishing effort 0.5	7	0.097	0.003	2676.000	29.689
Fishing effort 0.4 - Fishing effort 0.6	7	0.194	0.007	2676.000	29.689
Fishing effort 0.4 - Fishing effort 0.7	7	0.290	0.010	2676.000	29.689
Fishing effort 0.4 - Fishing effort 0.8	7	0.387	0.013	2676.000	29.689
Fishing effort 0.4 - Fishing effort 0.9	7	0.484	0.016	2676.000	29.689
Fishing effort 0.4 - Fishing effort 1	7	0.581	0.020	2676.000	29.689
Fishing effort 0.5 - Fishing effort 0.6	7	0.097	0.003	2676.000	29.689
Fishing effort 0.5 - Fishing effort 0.7	7	0.194	0.007	2676.000	29.689
Fishing effort 0.5 - Fishing effort 0.8	7	0.290	0.010	2676.000	29.689
Fishing effort 0.5 - Fishing effort 0.9	7	0.387	0.013	2676.000	29.689
Fishing effort 0.5 - Fishing effort 1	7	0.484	0.016	2676.000	29.689
Fishing effort 0.6 - Fishing effort 0.7	7	0.097	0.003	2676.000	29.689

Fishing effort 0.6 - Fishing effort 0.8	7	0.194	0.007	2676.000	29.689
Fishing effort 0.6 - Fishing effort 0.9	7	0.290	0.010	2676.000	29.689
Fishing effort 0.6 - Fishing effort 1	7	0.387	0.013	2676.000	29.689
Fishing effort 0.7 - Fishing effort 0.8	7	0.097	0.003	2676.000	29.689
Fishing effort 0.7 - Fishing effort 0.9	7	0.194	0.007	2676.000	29.689
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Fishing effort 0.8 - Fishing effort 0.9	7	0.097	0.003	2676.000	29.689
Fishing effort 0.8 - Fishing effort 1	7	0.194	0.007	2676.000	29.689
Fishing effort 0.9 - Fishing effort 1	7	0.097	0.003	2676.000	29.689

Table S6. Temporal data from 2009-2022 of arapaima population used in the metapopulation model followed by the corresponding carrying capacity (K) (See main text: Methods - Metapopulation Model for details on how K was estimated). Numbers correspond to the mature arapaima individuals in each lake, counted by local fishermen in each year. Temporal data was compiled from reports from the local fishing association submitted annually to the federal environmental agency (Insituto Brasileiro do Meio Ambiente - IBAMA) as part of the Fishery Co-Management.

Territorial management	**Category**	**Lake**	**2009**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**K**
RESEX Medio Jurua	protected/subsistence	Branco	11	42	100	51	30	13	60	57	63	121	24	160	111	71.53
RESEX	protected	Dona Maria			45	72	51	78	20	21	52	42	92	57	42	52.68
RESEX Medio Jurua	protected/subsistence	Janiceto			0	2	13	22	15	16	32	23	24	17	13	21.01
RESEX	protected	Manaria	683	691	673	537	770	90	114	346	86	334	408	396	241	367.42
RDS Uacari	protected	Mandioca				259	244	266	245	294	350	249				274.46
RDS Uacari	protected	Marari			56	676	531	583	706	702	428	456	712	925		629.23
RESEX Medio Jurua	protected	Onça				4	3	19	11	3	21	17	61	17	18	21.59
RESEX Medio Jurua	protected	Sacado do Juburi	29	32	134	357	375	620	600	499	528	929	708	1053	849	736.09
RESEX Medio Jurua	protected	Samaúma	26	138	191	280	292	321	267	288	240	596	408	555	527	412.50

RDS Uacari	protected	Santo Antônio	2	5	30	56	26	65	85	49	149	63.35

Figure S1. Distribution of centrality metrics of the Arapaima spatial metapopulation network based on the 31 studied lakes from Middle Juruá River Basin, Western Brazilian Amazon. Total node degree (left panel) corresponds to the sum of all edges (coming in and going out links) of each lake; node out-strength is the quantitative version of out-degree, here used as a proxy for Arapaima dispersal.

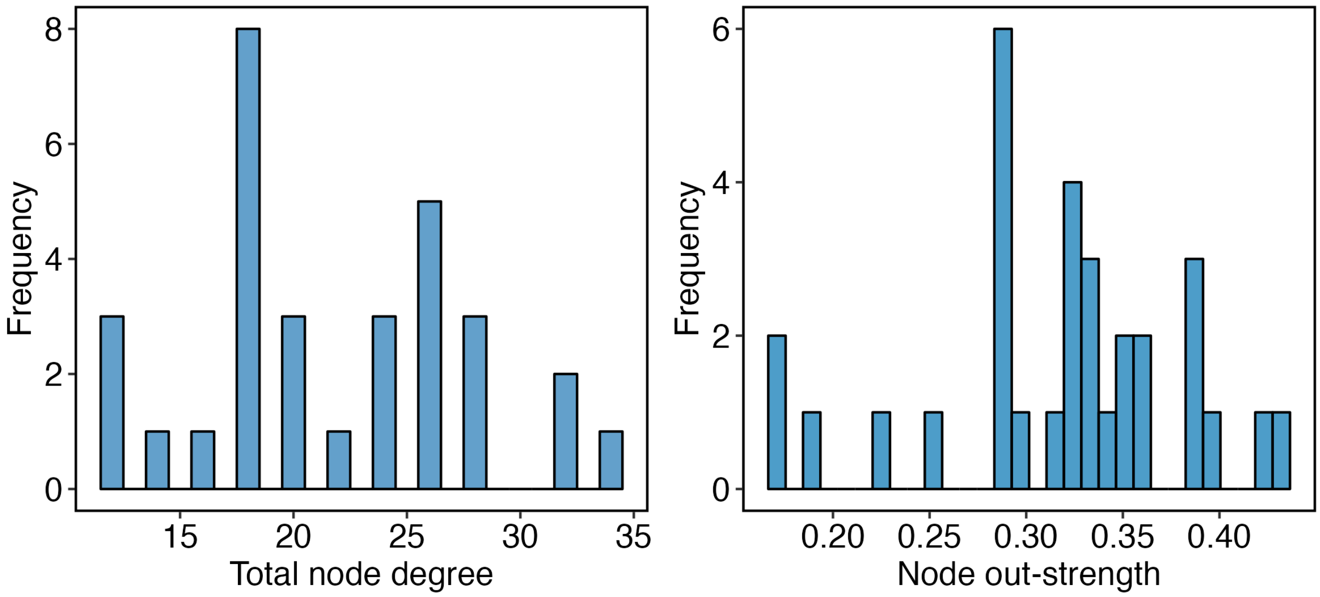

Figure S2. Differences between protected and unprotected lakes in the gradient of increasing fishing effort across the seven scenarios of Fishery CoManagement (FCM). Each dot represents the protected-unprotected log difference in the back-transformed Estimated Marginal Means for a specific scenario, adjusted according to the other variables in the model. Values below zero indicate that protected lakes have less fish than unprotected lakes; values above zero show the opposite. Details of each scenario can be found in Table 1.

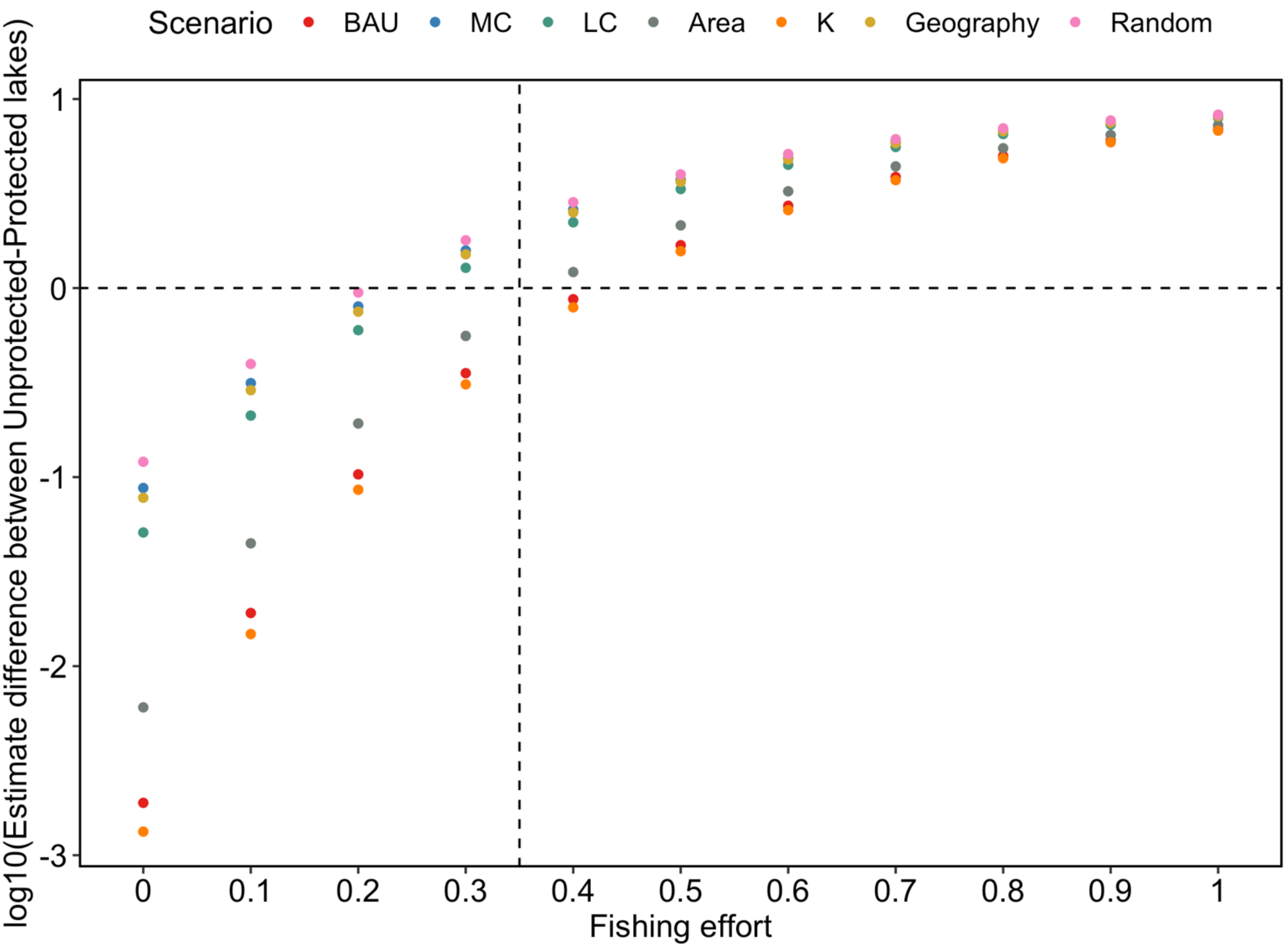

Figure S3. Population dynamics of Arapaima modelled from empirical data. The procedure to calculate the *r* and *K* parameters fitted to a logistic growth function defined above, was only applied to time series with enough observations (N = 10), defined as having at least seven consecutive values.

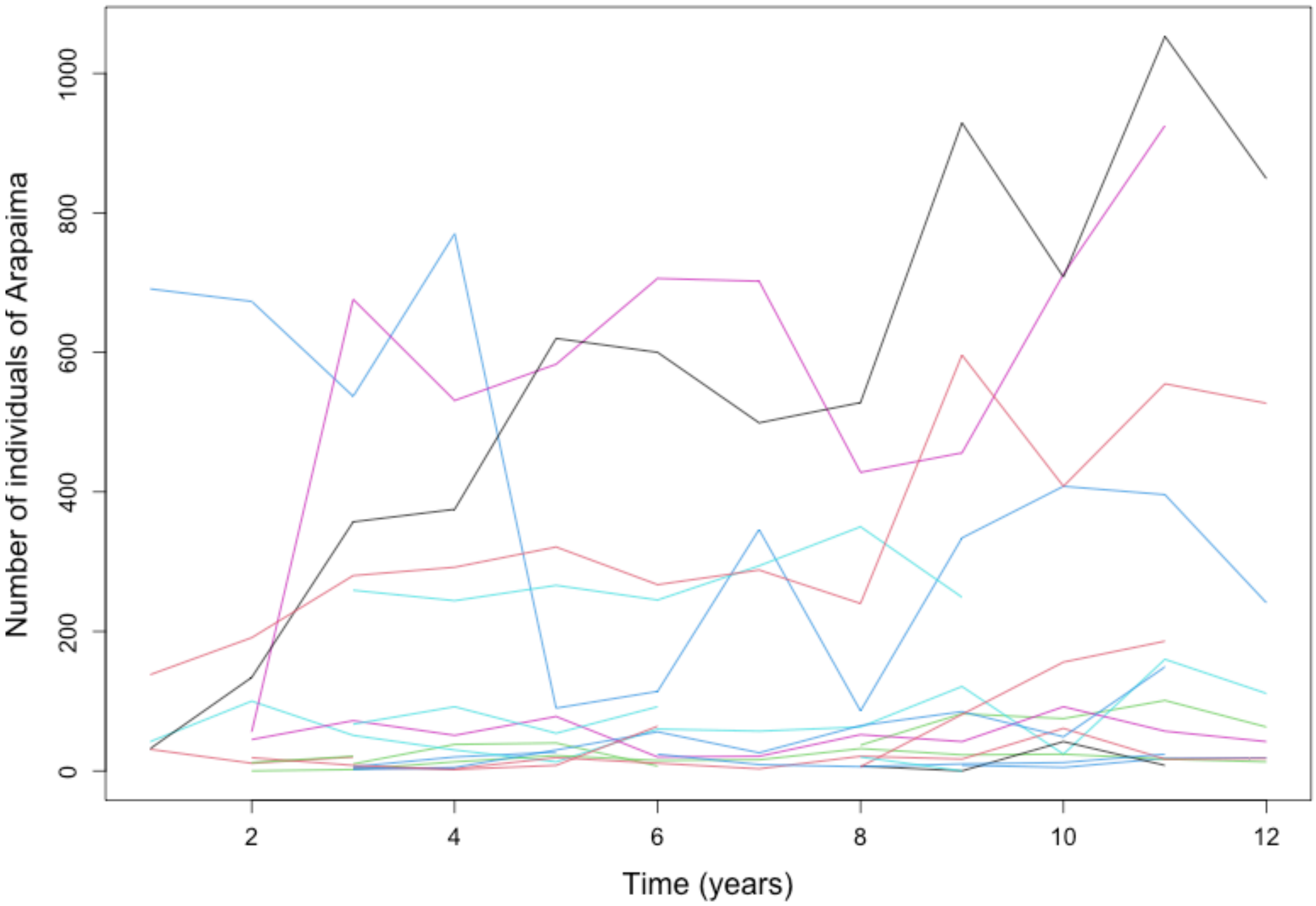

Figure S4. Simulated population dynamics of Arapaima. Each local lake population dynamic is governed by a Ricker logistic equation. See Methods in the main text for further details.