Ambio 2022, 51:678–690
https://doi.org/10.1007/s13280-021-01575-1

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RESEARCH ARTICLE

Institutional effects on ecological outcomes of community-based management of fisheries in the Amazon

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Received: 18 June 2020 / Revised: 13 February 2021 / Accepted: 9 May 2021 / Published online: 16 June 2021

Abstract Communities throughout the globe are increasingly being given the responsibility of resource management, making it necessary to understand the factors that lead to success in community-based management (CBM). Here, we assessed whether and how institutional design principles affect the ecological outcomes of CBM schemes for *Arapaima* sp., an important common-pool fishery resource of the Amazon Basin. We quantified the degree of presence of Ostrom's (Science 325:419–422, 1990) institutional design principles in 83 communities using a systematic survey, and quantitatively linked the design principles to a measure of ecological outcome (arapaima density) in a subset of 39 communities to assess their influence. To understand regional patterns of institutional capacity for CBM, we evaluated the degree of presence of each principle in all 83 communities. The principle scores were positively related to arapaima density in the 39 CBM schemes, explaining about half of the variation. Design principles related to defined boundaries and graduated sanctions exerted the strongest influence on the capacity of CBM to increase arapaima density. The degree to which most principles were present in all 83 communities was generally low, however, with the two most influential principles (defined boundaries and graduated sanctions) being the least present of all. Although the roles of the other principles (management rules, conflict resolution, collective action, and monitoring systems) are probably important, our results indicate that efforts aimed at strengthening the presence of defined boundaries and graduated sanctions in communities hold promise to improve the effectiveness of arapaima CBM regionally.

Keywords Arapaima · Conservation prioritization · Governance · Small-scale fisheries · Social–ecological systems

INTRODUCTION

Community-based management (CBM) arrangements in which government authorities and resource users share responsibility over management of common-pool resources (Horwich and Lyon 2007; Brooks et al. 2012) are thought to create incentives for people to comply with rules (McCay and Acheson 1987; Jentoft 2000). Many rural resource-dependent communities throughout the globe are thus increasingly being given the responsibility of resource management (Brooks et al. 2012), making it necessary to understand the factors that lead to success in CBM.

The efficacy of CBM is thought to depend on institutional factors that can increase the likelihood that communities of resource users can avoid the tragedy of the commons (Baland and Platteau 1996; Agrawal 2001). Among these factors, Ostrom's (1990) institutional design principles, which are higher-level concepts that must be operationalized according to local conditions, are widely accepted to constitute useful guides (Cox et al. 2010). Several studies have used Ostrom's principles to analyze the socio-economic and institutional dimensions of CBM at fairly localized scales, advancing understanding about the emergence and robustness of CBM and emphasizing the

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Supplementary Information The online version of this article (https://doi.org/10.1007/s13280-021-01575-1) contains supplementary material, which is available to authorized users.

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complexity of the social processes involved (Steins and Edwards 1999; Gautam and Shivakoti 2005).

Research has sought to understand the effects of institutional design principles on ecological outcomes of CBM by capturing variability in large sample sizes over large geographical regions, which is essential to assess the effect of different factors (Agrawal and Chhatre 2006; Cinner et al. 2012). However, while the incorporation of ecological considerations in the study of common-pool resources like small-scale fisheries is increasing (see Cinner et al. 2012), much less attention has been paid to CBM in inland fishing contexts (Smith et al. 2021). Yet, incorporating the effects of institutional factors on ecological conditions is challenging, with only one-third of all common-pool resource studies including ecological variables, according to Rissman and Gillon (2017).

One key area of uncertainty in the study of the relationship between institutional factors and ecological outcomes relates to what factors (e.g., design principles) are necessary or sufficient for a positive ecological outcome to emerge (Basurto et al. 2013). Some studies have suggested that the likelihood that a CBM can avoid the tragedy of the commons and govern their common-pool resource sustainably increases with the number of design principles that are present (Gutiérrez et al. 2011; Baggio et al. 2014). While that may be true in some cases, there is the additional issue that certain principles may exert more influence than others on outcomes (e.g., Persha et al. 2011; Fleischman et al. 2014; Leslie et al. 2015). Some studies have found that ecological outcomes depend on specific configurations of co-occurrence of the design principles (Gutiérrez et al. 2011; Baggio et al. 2014). In one study, ecological outcomes were positively associated with the participation of users in rulemaking (Persha et al. 2011). In another study, institutional design principles influenced livelihood and compliance outcomes but had little effect on ecological outcomes (Cinner et al. 2012). This type of variability in outcome variables makes it difficult to understand the causes behind the successes and failures of CBM (Leslie et al. 2015). Improved understanding of the effects of design principles on ecological outcomes is needed, particularly in inland tropical fisheries like the Amazon basin, where communities are highly heterogeneous in socio-ecological conditions (Barrett et al. 2001; Castello et al. 2013) yet highly dependent on riverine resources for the maintenance of their livelihoods and the absence of government authorities have yielded the governance of these fisheries to CBM.

Here, we assessed whether and how Ostrom's institutional design principles affect the ecological outcomes of CBM schemes for *Arapaima* sp., an important inland fishery of the Amazon Basin. Using systematic survey data collected in 83 communities, we quantitatively tested for linkages between Ostrom's design principles and arapaima densities, a measure of resource health, in the same communities. This allowed us to identify the most influential principles and quantify the relative presence of each principle in the studied CBMs. Such an assessment was necessary because for long a governmental agency in our study area in the lower Amazon region in Brazil has been considering implementing legislation for improved management of arapaima via CBM. Results from this research can shed light on which institutional factors could be the focus of efforts aimed at promoting the success of CBM for arapaima.

MATERIALS AND METHODS

Study approach

To assess the institutional design principles that affected the capacity of CBM schemes to sustainably manage arapaima populations, we first quantified the presence of Ostrom's (1990) institutional design principles in 83 communities using a systematic survey. We used data on the density of arapaima populations in a subset of 39 of those 83 communities to assess the degree of influence of each design principle on the density of arapaima populations through a regression analysis. We used the results from the regression analysis to identify the principles that were most influential on the success of arapaima CBM. In order to understand large-scale patterns of institutional capacity for CBM, we used data on the presence of the design principles across all 83 communities to identify institutional strengths and weaknesses in the region.

Study area

Lower Amazon floodplains and communities

Our study focused on arapaima (or pirarucu) fisheries in floodplains of the lower Amazon River near the city of Santarem, in Pará State, Brazil (Fig. 1). Here, the floodplain is seasonally inundated by flood pulses with an annual average of 6.2 m in amplitude (Junk et al. 1989). The floodplain comprises a mosaic of habitats, including lakes and channels that border the main river channel, as well as extensive areas (90%) of grasslands (macrophytes) and areas (13%) covered by forests (Hess et al. 2015).

All communities in the study area shared roughly the same similar physical and organizational structures allowing this study to explain differences in their governance capacity primarily through differences in the ways in which individual communities organized to manage arapaima populations. The studied communities ranged in size

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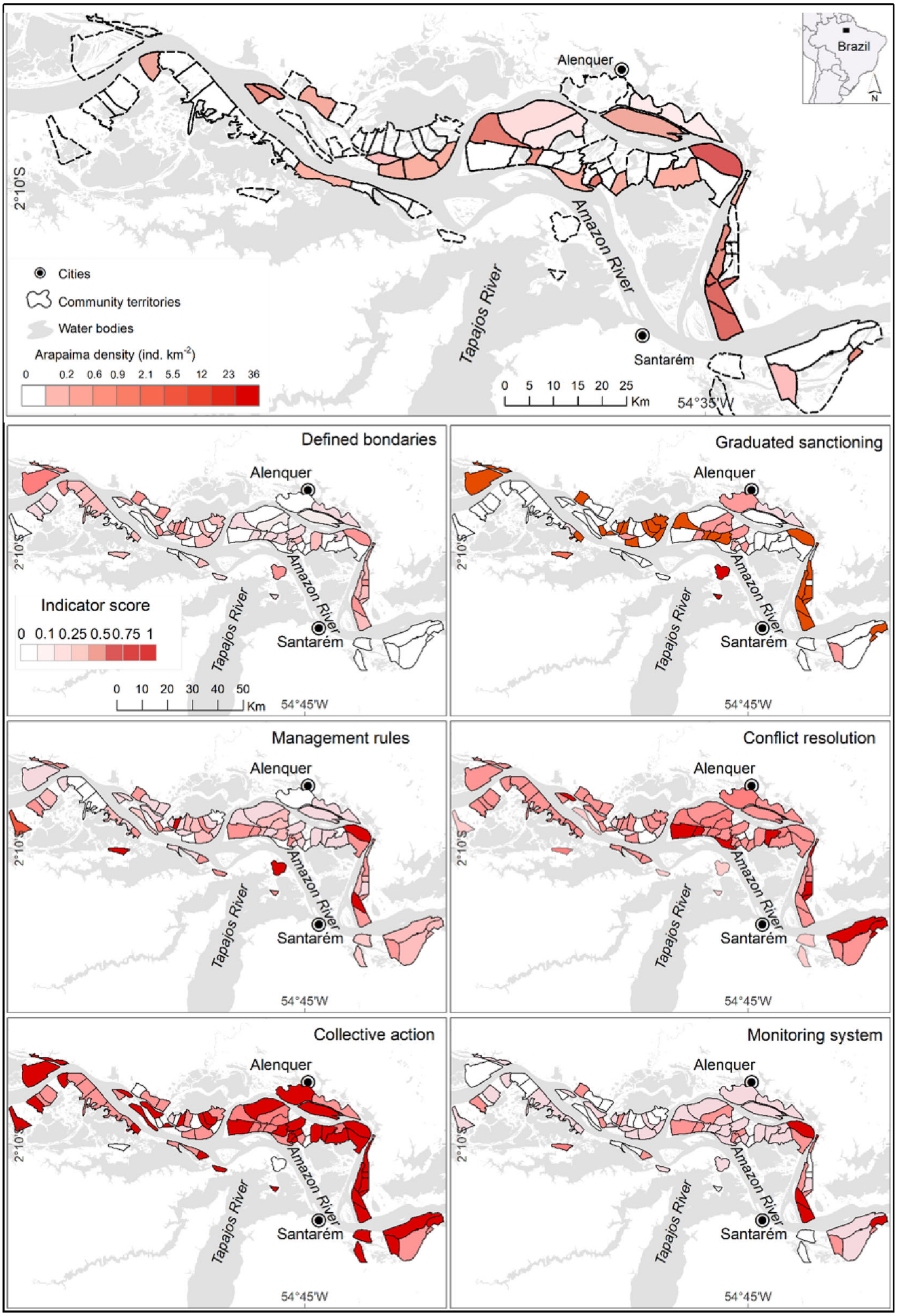

Fig. 1 The lower Amazon region in Brazil. Top figure shows the 83 studied communities areas (dotted lines) and the distribution of arapaima densities in a subset of 39 communities (continuous lines and shaded area). The bottom figures indicate the distribution of the indicator scores for the six design principles measured in the 83 communities (shaded areas)

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between 40 and 130 houses (McGrath et al. 2008). Communitt locations vary from the uplands adjacent to the floodplains to the floodplain facing the main river channel. In terms of infrastructure, the communities overall usually have a chapel, a community center, and one or more schools. Community organizations evolved from a Catholic Church movement that for over the last 50 years trained community leaders, facilitated implementation of leadership based on a presidential system, and organized meetings and other activities to develop the political organization of community members.

In the studied communities, fish represents a major source of animal protein (Isaac and Almeida 2011). Fisheries take place in both floodplain habitats and main river channel in varying degree depending on the community localization. Fishers undertake fishing trips targeting multiple taxa using canoes powered by engine or paddle, and use different gears including gillnets, castnets, harpoons, and handlines, among others (Castello et al. 2013). Catches comprise about 40 species but a few species, including arapaima, account for most of the total catches. In addition to commercial and substance fishing, households engage in other economic activities with varying combinations of land and resource use, including traditional annual crops (manioc, corn and beans), horticulture, and small and large animal husbandry (mostly chickens and cattle) (de Castro and McGrath 2003).

CBM of arapaima

Floodplain communities in the Amazon developed policies and institutional arrangements for fisheries co-management in response to expansions of commercial fishing fleets in 1970s, which led to increased pressure on floodplain lakes. The communities negotiated intercommunity agreements defining who had access to community lakes and specified acceptable fishing practices. This movement triggered a process that transformed fisheries management policy that established territorial rights of the communities, their right to define management rules, and to regulate grazing of cattle on floodplain grasslands.

As a result, during our study, between 2009 and 2010, virtually all communities in the study area were engaged in two types of CBM: fishing agreements and Agro-Extractivist Settlement Projects (known as ‘PAEs’). The first type of CBM, fishing agreements, has restrictions on fishing gear, locations, and seasons that are officially recognized and that were established by local communities in the 1990s with the help of governmental and non-governmental organizations. Fishing agreements do not permit communities to control access to the fishing areas but establish a series of rules that any fisher must follow. These rules limit fishing pressure by city-based fishers in floodplain habitats (de Castro and McGrath 2003). The second type of CBM, the PAEs, builds on fishing agreement experiences placing restrictions on fishing gear, locations, and seasons but also grants collective land concession to the communities in exchange to the commitment to sustainably use natural resources in their respective areas (McGrath et al. 2008). In general, fishing-agreement communities in the region were incorporated into the PAEs. PAE and fishing-agreement communities both have representatives that implement fishing rules and take issues not solved at the community level to the next higher level of governance, which are the Regional Fisheries and PAE Councils. Between 2009 and 2020, the responsibilities for fisheries management policy are being transferred among Federal and State governmental agencies. From IBAMA, the federal institute for environment, the responsibility was transferred to several other agencies, and currently is under state agencies, SEMAS in the case of Pará. All the agencies faced the same challenges of being under-funded and under-staffed to performs their duties.

Arapaima have been the focus of CBM in the Amazon because they have high social, cultural, and economic value. These fish have historically sustained intense fishing pressure as they expose their bodies out of water to harpoon-specialist fishers when they breathe air obligatorily every 5–15 min (Verissimo 1895; Castello et al. 2015). In addition, arapaima is profitable as they grow up to three meters in length and 200 kg in weight and achieve high market prices. The Brazilian environmental government agency (IBAMA) implemented minimum size (1.5 m total length, TL) and closed season (December–May) limits in the 1980s, and even moratoria in some states in the 1990s, but poor enforcement of regulations has allowed for about three-fourths of the arapaima harvests to be illegal (Cavole et al. 2015). Consequently, arapaima populations are now widely overexploited and even locally extinct in some areas (Castello et al. 2015). Consequently, *Arapaima gigas* is enlisted in the IUCN Red List and in the Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (IUCN 2014). Two other species, *Arapaima agassizii* and *Arapaima leptosome,* are recognized by the Brazilian Red List as ‘Data Deficient’ (Stewart 2013; ICMBio 2018). Yet, studies have shown the existence of genetically distinct populations thought the Amazon Basin (Fazzi-Gomes et al. 2017; Farias et al. 2019). Although there is no evidence that distinct species occur at the scale of our study, we acknowledge that there are taxonomic uncertainties and consider the precautionary principle to refer here to arapaima only at the genus level.

These trends have spurred the development of CBM schemes for arapaima, in part because these fish are conducive to local management. The small home range of arapaima enables management at the community scale

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(Castello et al. 2011), while their obligate air breathing behavior allows expert fishers to count them and use the data to regulate harvests (Castello 2004). Their body growth and reproductive traits in turn allow their populations to sustain moderate fishing mortality and even to quickly recover from overexploitation when size and season and harvests limits are followed (Arantes et al. 2010; Castello et al. 2011).

Arapaima fishing is currently permitted in the State of Pará based on season and size limits. The Pará government is currently reviewing legislation passed by the state assembly to regulate arapaima management following the regulatory system used in the state of Amazonas. Once signed into law, arapaima fishing will only be permitted in communities that undertake annual counts of arapaima populations in managed lakes and use the count data to determine annual harvest quotas. The impetus for this new legislation is data showing that arapaima populations managed via this system have recovered from overexploitation and fishers' revenues have increased (Castello et al. 2011; Campos-Silva and Peres 2016; Petersen et al. 2016). Results from this study will contribute to improving the effectiveness of arapaima CBM in our study area.

Data collection

Institutional design principles

We considered the following institutional factors: defined boundaries, congruence between rules and local conditions, collective action arrangement, monitoring system, graduated sanctioning, and conflict resolution mechanism (Table 1). These factors were used before to understand the dynamics of CBM for arapaima (Castro 2000; de Castro and McGrath 2003; McGrath et al. 2008; Castello et al. 2009; Table 1). We did not consider principles related to 'minimum recognition and right to organize' and 'nested enterprises' because in Brazil these principles are determined by federal-level policies and were present in all communities (see Table 1 for principles' descriptions and details). We established indicators measuring different aspects comprised by each principle, and we scaled the indicators from zero, to denote absent principles, to one, to denote present principles (Table 1). A maximum score of one was set for principles that were deemed to be 'fully present' in order to test (see below) the null hypothesis that all principles have equal weight on the CBM outcome. For the principle related to the monitoring systems, for example, we determined three indicators: one measuring the presence of a monitoring system of fishers' behavior (i.e., CBM rules were enforced by the community), and two measuring the presence of monitoring systems of the resource (i.e., arapaima populations were monitored, and arapaima catches were monitored). Because monitoring of the resource and of fishers' behavior are both necessary to satisfy this principle, we attributed equal weights (0.5) for the indicators related to resource and fishers' behavior aspects, with the two indicators for monitoring of the resource each having a 0.25 weight (see Table 1 for other principles and indicators).

We scored the indicators based on a survey conducted between July 2009 and September 2010 in the study area, near Santarem (Fig. 1). From about 100 communities located in the region, we included 83 (encompassing 1897 km^2) in the survey. We selected these communities because fishers indicated willingness to participate in the research. These 83 communities showed large variability in degree of development in CBM and arapaima population density; some communities had it implemented only nominally (i.e., implemented rules but did not abide by them) and others had it quite developed over decades of work (i.e., several rules implemented and strictly enforced, and backed by strong leadership, ties to regional institutions, etc.; McGrath et al. 2008; Castello et al. 2015). To collect our data in the 83 communities, we interviewed a total of 180 expert fishers, with an average of 2.5 fishers ($\pm$ 1.6) per community. The interviewed fishers were selected by their respective community leaders and peers as being experts on arapaima fisheries, and we are unaware that their responses could have had any specific biases, so a priori we assumed their responses were accurate, although some biases might have been possible.

For each community, we summed all indicator scores for each of the six design principles assigned for each fisher interviewed. Fisher responses for the same communities tended to be consistent among themselves with 84% of them being identical; in the only 16% of all responses where fishers' responses for the same communities differed, we averaged their scores to have a more nuanced understanding of the performance of the management system as perceived by them. Our interpretation of these inconsistencies is that they stemmed from different perspectives, as illustrated by the following example for principle 1. Whereas the presence of a well-defined boundary may seem straight forward to be classified as present or absent, there are cases where communities have an agreement establishing that they do not share fishing areas with outside fishers, but this agreement may not be recognized, or respected, by outside fishers. Thus, for any principle, depending on their perceptions, fishers can attribute the indicator for the principle to be absent, or present. Again, averaging out fishers scores for those few cases where responses were inconsistent, balanced divergent responses to provide a more realistic measurement of the degree of presence of the principle (Table 1).

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Table 1 Description of each Ostrom (1990) principle for sustainable governance of common-pool resources and the respective measurable indicators. The measurement weights assigned to each indicator are shown in parenthesis. Principle definitions are based on Ostrom (1990) and indicators are based on Castro (2000), Castello et al. (2009), McGrath et al. (1993), de Castro and McGrath (2003), and McGrath et al. (2008). Principles 7 (Minimum Recognition and Right to Organize) and 8 (Nested Enterprises) state, respectively, that central governments should formally authorize and recognize the rights of appropriators to devise their own institutions, and the need for nested organization of management tasks in multiple levels and organizations. These principles were not included because they are determined by federal-level policies and were present in all communities

Principle (Institutional factor)	Description and indicators
P_1: Defined Boundaries	Description: It states the need for clearly defined boundaries of the resource and its users. We asked the interviewees if the communities share fishing areas with fishers from neighboring communities or other regions and if user group with whom the resource was shared was well defined.
	Indicators:
	1: The community did not share fishing areas with fishers from neighboring communities or other regions (0.5)
	2: The community shared fishing areas with fishers from neighboring communities or other regions, but the shared use was recognized by the community and was done in agreement between the local and outside fishers (0.5)
P_2: Congruence between rules and local conditions	Description: It states that rules of resource access and use (e.g., limits to gear, catch, areas, etc.) should match local conditions. In the case of arapaima fishing, this means assessing the extent to which rules of harvest existed and if they contributed to producing sustainable arapaima fisheries. To measure this principle, we determined six indicators. We asked the interviewees if their communities have established fisheries rules, and if the rules, when established, were followed by the fishers. We also asked if the community established local rules specifically for arapaima fisheries that were followed by fishers. Finally, we assessed if government rules for arapaima fisheries of closed season (Dec.–May) and minimum size limit (150 cm TL) were followed.
	Indicators:
	1: CBM rules were established (0.17)
	2: CBM rules were followed (0.17)
	3: CBM rules for arapaima fisheries were established (0.17)
	4: CBM rules for arapaima fisheries were followed (0.17)
	5: Closed season (Dec–May) was followed (0.17)
	6: Minimum size limit (150 cm TL) was followed (0.17)
P_3: Collective action arrangements	Description: It states the need for a functional collective action arrangement where most individuals affected by the rules can participate in the definition and modification of the rules. To measure this principle, we determined two indicators. We asked the interviewees who were the decision-makers in their communities, and if mechanisms were available to adapt the rules, such as community meetings.
	Indicators:
	1: All community members could participate in defining and modifying the rules (0.5)
	2: Mechanisms to change the rules, such as community meetings, were available and used (0.5)
P_4: Monitoring system	Description: It states the need for monitoring the resource and behavior of the fishers. To measure this principle, we determined three indicators. We asked the interviewees if the community enforced rules for arapaima fisheries and if the community monitored arapaima fisheries and populations.
	Indicators:
	1: CBM rules were enforced by the own community (0.5)
	2: Arapaima populations were monitored (0.25)
	3: Arapaima catches were monitored (0.25)
P_5: Graduated Sanctioning	Description: It states the need for graduated sanctions of rule offenders. To measure this principle, we determined two indicators. We asked the interviewees if those who break the rules were punished, and if the punishment varied in degree depending on the re-incidence and/or on the severity of misconduct.
	Indicators:
	1: Rule offenders were punished (0.5)
	2: Punishment varied in degree depending on the severity and frequency of the misconduct (0.5)

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Table 1 continued

Principle (Institutional factor)	Description and indicators
P_6: Conflict Resolution Mechanism	Description: It states the need for a rapid and low-cost conflict resolution mechanism. We determined two indicators: we asked the interviewees if conflict resolution mechanisms existed for fisheries management. We also asked how many mechanisms to solve fisheries conflicts existed and were available in the community. We assumed that large numbers of mechanisms fostered conflict resolution more than small numbers of mechanisms. This assumption is reasonable because when one low-cost mechanism for resolving conflict fails, users are able to access a different low-cost mechanism.
	Indicators:
	1: There were accessible manners of solve problems (0.1)
	2: Two or more manners of solve the conflicts (e.g., different types of community forums) were available (0.9)

Ecological outcome

We chose population density as our measure of ecological outcome because it is the most important indicator of health of an exploited fish population. We measured population density of arapaima in each of the 39 communities using direct counts. This subset of about 47% of the 83 communities for which we assessed the design principles possessed data on arapaima density as described in Castello et al. (2015), encompassed a large geographical area (1040 km^2), and included communities willing to permit survey work of arapaima populations in their respective floodplain lakes. Arapaima density data were collected using a scientifically tested and standardized method to count the individuals at the moment of their obligate air breathing (Castello 2004), as follows. Each fisher counted arapaima individuals in a lake area ranging from 0.2 to 1.0 ha over a 20-min period, which corresponds to the maximum interval between aerial breaths. Counts were conducted synchronously by different fishers in each lake area until the entire area of the lakes was covered. Arapaima counts done by groups of fishers vary by 10–30% relative to real values (Castello 2004; Arantes et al. 2007). Accurate population estimates of this type are rare for fish population assessments. Arapaima abundance data for each community were converted into density estimates on a per floodplain area (ind/km^2) based on the area of community territories as determined in fishing agreements and PAEs documents, and as done in other studies (Castello et al. 2011, 2015).

Data analysis

Assessing the effects of institutional factors

To assess whether all design principles affected ecological outcomes and whether they had similar effects, we tested for effects of all principles together using a multiple regression analysis. The regression was fit under the a priori assumptions that (i) all principles could affect the ecological outcome and (ii) their effects had similar magnitudes. If a given principle were to have no effect or have a larger or smaller effect than the other principles, which is plausible given previous studies, such effects would be shown statistically. The multiple linear regression had arapaima population density (A, ind/km^2) as the response and indicator scores for each of the six principles (e.g., I_1, I_2, …, I_8; Eq. 1), as explanatory variables. The model was fit using a gaussian family distribution and included identity link function. We assessed the relative effect (or weight) of each principle on arapaima density based on the magnitude, or effect size, of the fitted regression coefficients (i.e., β_i):

$$A = \alpha + \beta_1 I_1 + \beta_2 I_2 + \beta_8 I_8 + \varepsilon \quad (1)$$

We log-transformed all data to achieve normality in the data; we computed all possible models and parameter estimates through model averaging (Anderson and Burnham 2002). In a model averaging approach, the regression parameters are derived from weighted averages of corresponding values across all models that achieve similarly high levels of support (Anderson and Burnham 2002). The coefficients (i.e., β_i) and standard error estimates were not conditional on a single model, but were derived from weighted averages of corresponding values across all subsets of models that had cumulative Akaike weighs < 0.95 regardless of whether the variable appeared in the model (Anderson and Burnham 2002). We assessed the averaged model with respect to potential multicollinearity among variables (Variance Inflation Factors, Myers and Myers 1990), independence of errors (Durbin–Watson tests), and the distribution of model errors (Shapiro–Wilk and residual plots). All analyses were performed in R v. 3.2.0 using the packages ‘glmulti’ and ‘MuMIn’ (Barton 2009; Calcagno 2013).

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Assessing institutional strengths and weaknesses in arapaima CBM

To assess the institutional strengths and weaknesses of arapaima CBM, we evaluated the degree to which each principle was present in all 83 communities. To do this, first we calculated the maximum weighted principle scores that would hypothetically be assigned to each community if all indicators for the principles were 'fully present' (i.e., communities would receive maximum principle scores for the principles, multiplied by its respective regression coefficient). Then, we averaged out the principle scores assigned to all 83 communities, and weighted them by their respective regression coefficients. Finally, we evaluated the degree of presence of each principle by calculating the percent difference between the hypothetical maximum weighted principle scores and the average weighted principle scores.

For example, for the principle related to defined boundaries, we calculated its hypothetical maximum principle score, which is the score a community would have if all indicator scores were fully present. The maximum score for this principle would be equal to the regression coefficient value of 1.74 (see Fig. 2). Then, we calculated the average score assigned for this principle across all 83 communities. Finally, we weighted this average score by the regression coefficient, which yielded the value of 0.67. The degree of presence of this principle across communities would be the percent difference between the hypothetical maximum weighted principle score (1.74) and the average weighted principle score (0.67), or 36% of the maximum weighted principle score.

RESULTS

Effects of institutional factors on the ecological outcome

The principle scores were positively related to arapaima density in the 39 CBM schemes (Figs. 1, 2, and 3), explaining about half of the variation ($R^2 = 0.52$; Figs. 2 and 3). The principles had different degrees of influence on arapaima density as shown by the variation of as much as one order of magnitude in the parameter coefficients (Fig. 2). The most influential principles were defined boundaries and graduate sanctioning, respectively, as indicated by their respective model coefficients (Fig. 2). The effects associated with conflict resolution, management rules, and collective action were uncertain, given that the standard errors of their coefficients slightly crossed zero. The coefficient associated with monitoring systems

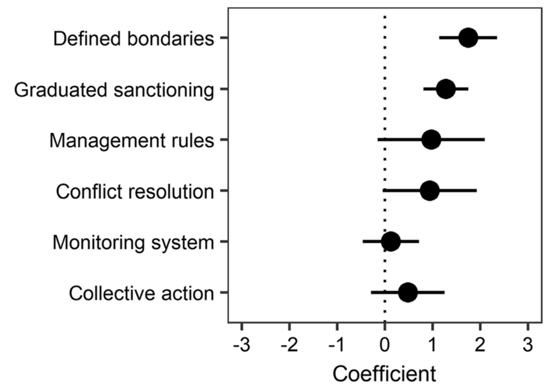

Fig. 2 Regression coefficients (β_i) and associated standard errors from the average regression model (Eq. 1) of arapaima density in a subset of 39 communities as function of the scores observed for the six design principles in the same communities

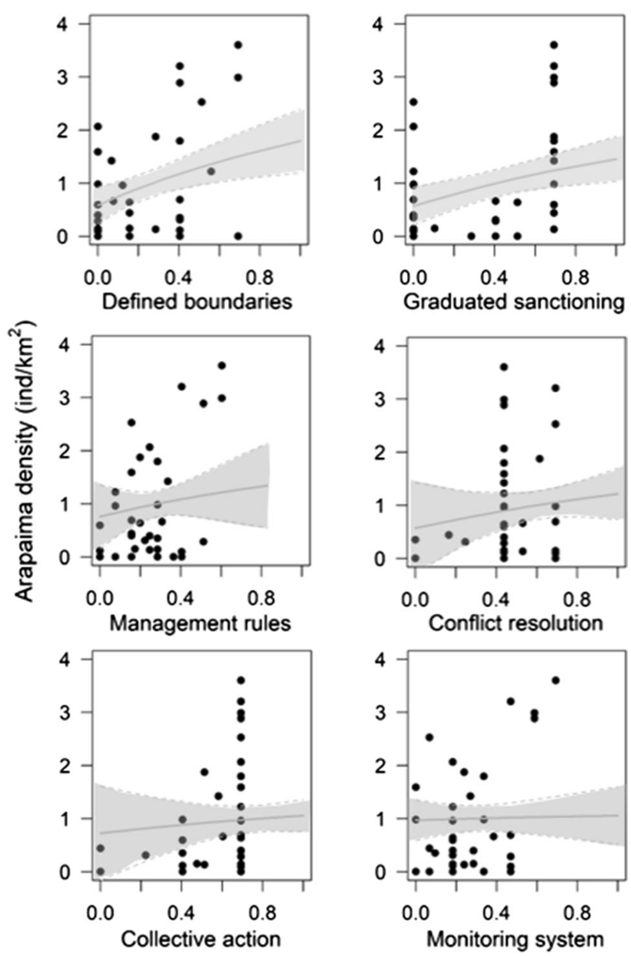

Fig. 3 Relationships between the indicators scores for the six design principles and arapaima densities (log) in the subset of 39 communities. Observed values (points) and fitted (continuous lines) and standard error (shade) estimations of the average regression model are shown

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was close to zero, so this principle had little if any influence on arapaima density (Figs. 2 and 3).

These results were based on a dataset that had high variability in CBM capacity for arapaima. Principle scores and arapaima densities greatly varied across the 39 communities (Fig. 1). The average indicator scores ranged from 0.27 (SD = 0.32) for the principle 'defined boundary' to 0.79 (SD = 0.25) for the principle 'collective action.' Arapaima densities ranged from 0 to 35.5 ind/km^2 across communities (average = 3.7 ind/km^2; SD = 7.6 ind/km^2; see Figs. 1 and 3 and Fig. S1). These results are robust as the final model met all assumptions. The Durbin–Watson statistic value was 2.5 and Variance Inflation Factors Values varied between 1.15 and 2.4, indicating no multicollinearity issues. Inspection of residual plots and Shapiro–Wilk test results ($W = 0.9673$, $p = 0.4$) indicated that errors were normally distributed.

Institutional strengths and weaknesses in arapaima CBM

The degree to which each principle was present in all 83 communities was generally low, being on average lower than 45% of the maximum weighted principle scores. Although defined boundaries and graduate sanctioning were the most influential principles (Figs. 2 and 3), their degree of presence in these 83 communities were only 36 and 45%, respectively (Fig. 4). Degree of presence of management rules was 34%, and that of monitoring system, which was the least influential principle, was only 26% (Fig. 4). Only the principles related to conflict resolution and collective action had a degree of presence higher than 50% of the respective maximum weighted principle scores (59% and 70%, respectively; Fig. 4).

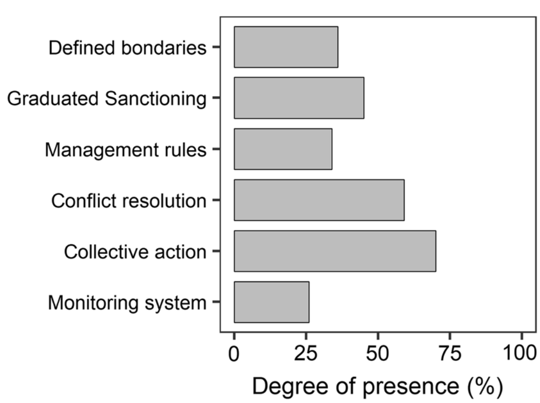

Fig. 4 Degree of presence of each principle relative to the maximum weighted score in all 83 communities

DISCUSSION

This is the first study in the Amazon to use data on ecological resource health to quantitatively assess the influence of the design principles on inland fishing CBM schemes. The results from our analysis indicate that all six design principles had positive effects on arapaima density, although the effects were not the same. The principles of well-defined boundaries and graduated sanctioning exerted strong positive influence on arapaima density, while three principles (management rules, monitoring system, and collective action) had weaker effects and lacked statistical significance in support of their effects. The view that emerges from these results advances understanding of institutional influences on ecological outcomes of CBM in riverine inland fisheries.

Consistent with our results, previous studies of CBM of arapaima and other fisheries in the Amazon based on descriptive methods and small sample sizes had shown that the design principles analyzed in our study tended to promote the sustainability of arapaima and other fish populations (Castro 2000; McGrath et al. 1993, 2008; Castello et al. 2009). Those studies emphasized that certain principles played key roles in sustainable management. Castro (2000) and McGrath et al. (1993) emphasized that monitoring systems of user behavior and collective action of management tasks addressed the pervasive problem of poaching by outsiders, allowing the efforts of CBM users to improve the health of fish resources. In line with many other studies elsewhere (e.g., Costello et al. 2008), those studies also emphasized that well-defined community boundaries was a pivotal factor for the success of CBM of fisheries in the Amazon because it allowed fishers to exclude outsiders and establish management control over their fish resources. Castello et al. (2009) built on those studies to assess the effect on management of having fishers themselves assess arapaima populations through counting of the individuals at the moment of aerial breathing. They showed that the involvement of fishers in resource monitoring was key to promote rule compliance and engagement of fishers in decision-making, thus prompting sustainable fishing practices.

We interpret that our results extend those findings and propositions by showing that well-defined boundaries and graduated sanctions have some of the strongest correlates of success in arapaima CBM. Well-defined boundaries and graduated sanctions are widely recognized as important determinants of institutional arrangement robustness in a variety of contexts beyond inland fishing (Gibson et al. 2005; Cudney-Bueno and Basurto 2009; Fleischman et al. 2010). These inferences are in line, however, with Campos-Silva and Peres' (2016) argument that the existence of well-defined boundaries, management rules, and

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enforcement systems were key to the recovery of arapaima fisheries in the Juruá River in the Amazon. They emphasized that the exclusion of outsiders was a key driver leading to increased arapaima populations. In our study area, the principles of well-defined boundaries and graduated sanctions are very difficult for the communities to implement. This is so because our study communities can have whole floodplain lakes within their own territories or may be located near large floodplain lakes that are shared with neighboring communities. Communities that have whole floodplain lakes within their territories have to impose catch restrictions (e.g., size limits) and punish rule offenders among their own respective community members. But communities that share floodplain lakes with neighboring communities face the additional challenge of imposing catch restrictions and punishing rule offenders among a larger, more diverse group of resource users, often requiring external stakeholders including members of non-governmental agencies to mediate conflicts between communities (McGrath et al. 2008). This is particularly difficult because, most state agencies (i.e., SEMA in Para State) that have the responsibility of enforcing governmental fishing regulations are unable to do so effectively because they lack the necessary financial and human resources. Consequently, government enforcement of regulations for arapaima fishing was very poor in the region during the study period, with an estimated 77% of the arapaima catch in weight being in violation of government limits of size and season of harvest; this pattern of poor rule compliance occurred even in communities engaged in co-management schemes (Cavole et al. 2015). Widespread illegal fishing and poor rule enforcement often force fishers themselves to enforce the rules and sanction rule offenders, even though they have no legal authority to punish rules offenders and find it difficult to do because they typically have strong kinship ties to other community members (Gillingham 2001).

While our results indicate generally weaker, more uncertain influences on arapaima density caused by management rules, conflict resolution, collective action, and monitoring systems, their importance should not be disregarded. Previous studies have also shown that certain principles are key to outcomes (e.g., Persha et al. 2011; Fleischman et al. 2014; Leslie et al. 2015), but that their influence may depend on the presence of other principles that apparently exerted weaker effects (Baggio et al. 2014). Accordingly, some studies have shown that management rules, conflict resolution, collective action, and monitoring systems have high practical importance (Cinner et al. 2012; Amrhein et al. 2019). Therefore, although in our study area, future research is needed to fully understand the effects of potential interactions among design principles, it is possible that, to some extent, those principles showing no statistical significance influences need to be in place in order to provide the basis for defined boundaries and graduated sanctions to become influential. This suggestion is not new. Management rules must be in place in order for users to be able to monitor the behavior of fishers and apply sanctions to rule offenders (Ostrom et al. 1994). Likewise, analyses of compliance (i.e., of how people conform to rules) have shown that enhanced participation of users in discussions and decisions regarding management rules legitimizes enforcement efforts, which in turn lead to declines in rule breaking (DeCaro et al. 2015) and the need to sanctioning rule offenders (Epstein 2017). The uncertainty and variability in variables associated with success outcomes in common-pool resources management requires caution to not disregard the potential roles of principles even for those lacking statistical evidence in support of their effects.

In general, the degree of presence of most principles in the region was generally low, with the two most influential principles, defined boundaries and graduate sanctioning, being the least present. This finding probably explains why arapaima populations in the 39 study communities were generally very low. A previous study that reported the same arapaima density data used herein concluded that arapaima populations were depleted in 76% of the fishing communities, overexploited in 17%, well-managed in 5%, and near unfished conditions in only 2% (Castello et al. 2015).

This finding also indicates that efforts aimed at strengthening capacity to perform arapaima CBM could focus on establishing the presence of defined boundaries and graduated sanctioning principles, while acknowledging the important roles played by management rules, conflict resolution, collective action, and monitoring systems. To achieve this, the communities that had higher degrees of presence of these principles, and hence higher arapaima densities, can serve as models. Such communities have developed and implemented strategies to regulate fishing behavior. For example, fishers in the community of São Miguel, which had the highest arapaima density, had established rules for arapaima fisheries, including the governmental closed season and restriction on the use of gillnet fishing gears. Fishers enforced these rules by taking turns to perform weekly patrolling activities, and received financial support from the other community members to cover patrolling expenses. Rule offenders received a warning notification, had their fishing gear confiscated, or lost rights to fish within the community territory, depending on the offense. Although government enforcement of regulations in the region had been poor (Cavole et al. 2015), its degree varies throughout the region, being somewhat stronger near major towns such as Santarém where São Miguel is located, so distance to towns probably is another factor that promotes CBM capacity.

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Building on these co-management schemes to strengthen CBM capacity for arapaima in the whole region requires additional efforts on the part of fishing communities and governmental and non-governmental organizations for them to "tango" together (Pomeroy and Berkes 1997). While collaborations among them in the past have spurred major advances (e.g., development of fishing agreements and PAE management plans), issues related to defined boundaries and graduated sanctions appear to still require substantial work. As mentioned above, many fishing communities have unclear boundaries or territory boundaries that intersect with those of neighboring communities. CBM users also lack support from governmental agencies to address problems of free-riding by local users and poaching by outsiders (e.g., often users from nearby cities). Strengthening the capacity of CBM for arapaima in the region thus also depends on increasing cooperation among stakeholder groups and bolstering the organizational, financial, and staff capacity of agencies responsible for management policy (e.g., SEMA) to define community boundaries and improve rule enforcement and sanctioning of rule offenders.

The approach we undertook in this study to assess the influence of institutional factors on ecological outcomes by linking design principles to resource density was relatively simple yet robust, so it could potentially be used to foster the systematic, cost-effective assessment of the social and ecological dimensions of CBM in other inland fisheries settings. It could be used to test hypotheses about the magnitude, relative contribution, and direction of relationships between institutional factors and ecological outcomes, as recommended by Agrawal (2001) and Agrawal and Chhatre (2006). However, we note that this approach should be viewed as a complement to traditional ethnographic and sociological analyses based on qualitative field observations or other multi-tier qualitative and quantitative approaches traditionally used to understand the complexity of governance systems (e.g., Ragin 2009; McGinnis 2011). A revised and improved approach to assess the influence of institutional factors on ecological outcomes could encompass a broader range of institutional factors such as the additional variables included in Ostrom's (2007, 2009) diagnostic framework for analyzing social–ecological systems.

CONCLUSION

Our study undertook a large-scale, systematic assessment that integrated institutional and ecological data to improve understanding of the roles of institutional factors on the ecological success of CBM. While our results are consistent with previous studies in the Amazon and elsewhere, they identify two principles, defined boundaries and graduated sanctioning, that are pivotal to promoting the success of arapaima CBM. The importance of focusing on these two principles is highlighted by the fact that they are the least present in the 83 studied communities. Efforts aimed at strengthening those two principles hold promise to improve the effectiveness of arapaima CBM. Nonetheless, given the complexity and associated uncertainty inherent of the dynamics of self-organizing governance systems, the roles of the other principles (management rules, conflict resolution, collective action, and monitoring systems) should be also considered.

Acknowledgements Funding was provided by Conselho Nacional de Desenvolvimento Científico e Tecnológico, Brazil (CNPq, processes 479434/2010-7 and 200893/2012-2), NSF-IFEWS (grant#1639115), NSF-CNH2 (BCS grant# 2009288), Instituto Nacional de Reforma Agrária, Brazil, the World Wildlife Fund for Nature, the Gordon and Betty Moore Foundation, the Applied Biodiversity Science Program (ABS/IGERT), Dissertation Fellowship and Tom Slick Fellowship from the Texas A&M University, and the USDA National Institute of Food and Agriculture, McIntire Stennis project [1026124]. A. Stronza, L. Fitzgerald, E. Ellis, E. Brondizio, B. Fulton, S. Villamayor, D. Stewart, and Ambio's anonymous reviewers and editor E. Andersson provided valuable comments to the previous versions of the manuscript. F. Sarmento and W. Rocha helped collect data.

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