Environmental Management (2009) 43:197–209
DOI 10.1007/s00267-008-9220-5

PROFILE

Lessons from Integrating Fishers of Arapaima in Small-Scale Fisheries Management at the Mamirauá Reserve, Amazon

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Received: 21 February 2007 / Accepted: 9 September 2008 / Published online: 23 October 2008

Abstract Fishers and small-scale fisheries worldwide have been marginalized historically. Now it is clear that integrating fishers in management processes is key to resource conservation, but it is less clear *how* to do it. Here, based on a literature review and new information, we present and analyze a case in which the participation of fishers in the management process was crucial in recovering an overexploited small-scale fishery for the pirarucu (*Arapaima* spp.) in the Amazon Basin, Brazil. In 8 years of experimental management, from 1999 to 2006, the population of pirarucu increased 9-fold (from about 2200 to 20,650 individuals), harvest quotas increased 10-fold (from 120 to 1249 individuals), and fishers' participation in the management process increased and they benefited from increased monetary returns. Additionally, the number of communities conducting the management scheme increased from 4 in 1999 to 108 in 2006, following the demands of fishers and regional government agencies. Based on our analysis, we suggest that the participation of fishers in the management of other small-scale fisheries in the world can be improved by focusing on (1) applying the knowledge and skills of fishers in resource monitoring and management, (2) bridging knowledge systems among all involved stakeholders, (3) collaborating with fishers that are interested in, and capable of conducting, resource conservation schemes, and (4) conducting management under conditions of uncertainty.

Keywords Brazil · Common property · Conservation · Developing countries · Local knowledge · Participatory research and management

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Small-scale fisheries are extremely important. They employ 50 of the world's 51 million fishers, produce about half of the global reported catch, and provide food, income, and livelihood to about 1 billion people (Berkes and others 2001, p. 223). They even are considered by some to be "our best hope for sustainable utilization of coastal resources" (Pauly 2006) because of their generally low operational costs and waste and high productivity per unit of money or fuel consumed (Thompson and FAO 1988).

Yet, small-scale fisheries worldwide face several problems. An open-access regime has lead to excessive fishing effort (Gordon 1954; McManus and others 1992), and put small-scale fisheries in conflict with large-scale fishing enterprises that often deplete their resources (Pauly 2006). Few small-scale fisheries have property or territorial rights (Aswani 2005; Castilla and Defeo 2001). The situation is

compounded by the fact that most small-scale fisheries are located in tropical developing countries where government-run environmental management capacity tends to be underdeveloped and even virtually inexistent (World Commission on Environment and Development 1987, p. 319). Moreover, managers and policy makers disregard small-scale fisheries because the fishers tend to be poor, come from ethnic groups, and have no political clout (Pauly 1997). Management agencies collect incomplete statistics because they lack human and financial resources to do it (Mahon 1997), and because small-scale fisheries tend to be physically remote (Pauly 1997). Even fisheries science ignores small-scale fisheries, as evidenced by a dearth of studies in that discipline (Mahon 1997). There are studies on small-scale fisheries in fields such as anthropology and sociology, but those have failed to produce models useful for policy-making (Pauly 2006). Thus, it is not surprising that most small-scale fisheries of the world now are thought to be poorly managed or becoming increasingly overexploited (Berkes and others 2001, p. 224).

How can we promote the conservation of small-scale fisheries? Several studies have shown that fishers' participation in management processes can contribute to the conservation of small-scale fisheries in several ways (e.g., Martin-Smith and others 2004). They can provide valuable knowledge on the biology and ecology of fish and fisheries (Foale 1998; Haggan and others 2007; Huntington 2000; Johannes and others 2000; Moreno 2007; Neis and others 1999; Silvano and Begossi 2005), as well as social and human capital (e.g., networking and collective action) that is critical for effective management. Fishers provide the only source of control in large regions of the tropical developing world, supplanting nonexisting management capacity (Johannes 1978, 1998). Now, fishers have become essential elements of so-called co-management and community-based management schemes (Pinkerton 1989), and their incentives to manage their own resources often are high, as they have few economic alternatives. Studies have shown that fishers work cooperatively toward resource use conservation, provided that the right circumstances are present (Cinner and others 2007; McCay and Acheson 1989).

However, it is less clear how exactly the participation of fishers in management can help establish sustainable resource use. Some argue that "full stakeholder awareness and participation contributes to credible, accepted rules that identify and assign the corresponding responsibilities appropriately" (Costanza and others 1998). However, levels of stakeholders' participation have been shown to depend on economic and social status, access to government offices, and education levels, among other factors (Agrawal and Gupta 2005; Oliveira 2002). Fishers merely might be informed of decisions, be providers of information, or play more inclusive roles as central partners (Berkes 1994). Moreover, it has been shown that "successful" participation of fishers in management requires (1) consideration of practices that are embedded locally, socioculturally, and historically (Aswani 2005; Baelde 2007), (2) a focus on the fishers, not the fish resource (Berkes and others 2001; Castilla and Defeo 2001), and (3) actual empowerment of fishers in decision-making (Nunan 2006), among others conditions (Pomeroy and others 2001). In particular, it has been shown that it is key to consider not only how to establish successful participatory management systems but also how they became successful (Chuenpagdee and Jentoft 2007).

Methods

We contribute to the above-reviewed body of knowledge by presenting and assessing a case in which the participation of fishers in management helped revert a typical situation of "tragedy of the commons" (Hardin 1968). Two questions were asked: "*Why* integrating fishers in management promoted success in this case?" and, more generally, "*How* it is possible to integrate fishers management so that their participation contributes significantly to fisheries conservation?" We described the case based on a review of the literature, new information and data, and our personal direct observations. The first two authors were involved in the case study since its early development in 1998 up to today. The first author (L. C.) conducted research on fishery ecology and stock assessments, and the second (J. P. V.) coordinated the whole scheme, including extension work with local communities and negotiations among institutions.

We analyzed the case in two steps. In the first step, we assessed the extent to which the participation of the fishers improved the effectiveness of the management scheme. We did this using the institutional design principles that are thought to be needed for sustainable governance of common property natural resources. Such principles have been proposed by Ostrom (1990), and experience has shown that they are reliable indicators of the conditions under which groups of users can manage natural resources sustainably (Agrawal 2001; Baland and Platteu 1996; Ostrom 1990; Wade 1988). Such principles are described briefly below and in more detail in Table 1A. Principle 1 requires that the boundaries of the resource and its users be defined clearly; Principle 2 requires that the resource be exploited sustainably; Principle 3 requires a functional collective action arrangement; Principle 4 requires that the resource and the behavior of fishers be monitored; Principle 5 requires that rule offenders be sanctioned; Principle 6 requires a conflict

Table 1 (A) Ostrom's (1990) eight institutional design principles for sustainable governance of common property resources and (B) assessment of the presence/absence of Ostrom's principles in the pirarucu fishery at Jarauá communities in Mamirauá before and after the participatory management scheme was implemented

A	Ostrom's institutional design principles for sustainable governance of resources	
	Principle	Description
1	Defined boundaries	Clear definition exists of both the individuals with rights to exploit the resource and the boundaries of the resource
2.	Congruence between appropriation and provision rules and local conditions	Appropriation rules are related adequately to ecological and socioeconomic conditions and to provision rules
3.	Collective action arrangement	Individuals affected by the rules can participate in modifying the rules
4.	Monitoring	The monitors auditing the resource and the behavior of appropriators are accountable to the appropriators or are the appropriators
5.	Graduated sanctioning	Appropriators who violate the rules are likely to be assessed graduated sanctions, depending on the seriousness and context of the offenses
6.	Conflict resolution mechanism	Appropriators and officials have rapid access to low-cost arenas to resolve conflicts
7.	Minimum recognition and right to organize	The rights of appropriators to devise their own institutions are not challenged by external government authorities
8.	Nested enterprises	Appropriation, provision, monitoring, enforcement, conflict resolution, and governance activities are organized in multiple layers of nested enterprises
B	Establishing the principles in the management for pirarucu	
	Before	After
1.	Present: zoning system	Present: as before.
2.	Absent: size limit and closed season violated	Present: fishers follow management rules and pirarucu populations are growing
3.	Present: opportunities existed for individuals to participate	Present: as before with increased participation
4.	Absent: fishers are appropriators but underreporting of illegal catch undermined monitoring system	Present: counts of pirarucu are made by the fishers themselves
5.	Absent: illegal fishing widespread among community fishers	Present but weak: sanctioning done by reducing fishing quota
6.	Present: regular meetings were attended	Present: as before
7.	Absent: fishing of pirarucu banned	Present: scheme provided legal permit to harvest pirarucu
8.	Present: three-layered scheme with communities, Mamiraua Institute, and IBAMA	Present: as before

Note: the evidence supporting the assessment is provided for each principle

resolution mechanism; Principle 7 requires formal recognition and authorization from central governments; and Principle 8 requires that management tasks be organized and distributed among institutions at multiple levels. Our assessment of the case study determined the presence or absence of each of Ostrom's (1990) eight principles (Table 1A) for the periods before and after the management scheme was implemented. In the second step of our analysis, we identified the means by which the participation of the fishers in the management process promoted the establishment, if any, of Ostrom's principles after the management scheme was implemented. Our goal was to derive generalizations on the integration of fishers in management that are useful for promoting sustainability in other small-scale fisheries.

The Pirarucu Fishery at Mamirauá

Study Area and Its People

Our case study is at the Mamirauá Sustainable Development Reserve (Fig. 1), which is located in the Amazon Basin, State of Amazonas, Brazil. The study area consists entirely of várzea, a type of floodplain that is subject to marked seasonal flooding; water levels vary about 12 m every year (Ayres 1995). The entire ecosystem is flooded during the flood, and only the main river, a few connecting channels, and lakes contain water during the dry season (Junk 1997). The reserve is inhabited by ribeirinhos, a term that applies to the indigenous but non-Indian rural inhabitants of the margins of the Amazon Basin (Moran 1984).

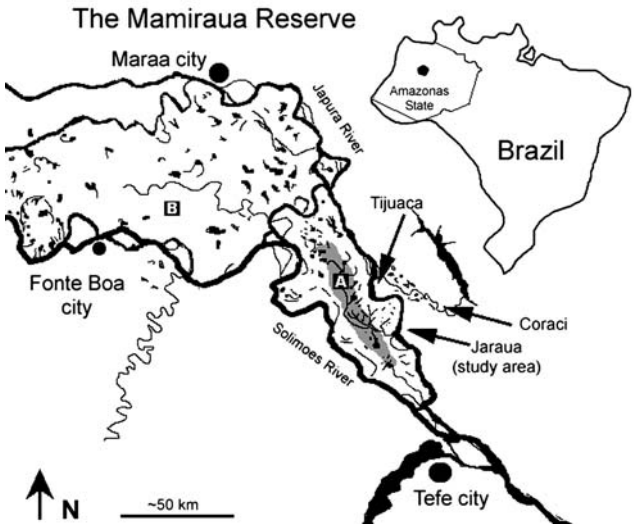

Fig. 1 Map of the Mamirauá Reserve, the Jarauá communities, and other key cities and community areas of the region. Lines denote water bodies of the várzea, including main river channels, connecting channels, and lakes and open lakes. The Mamirauá Reserve includes areas A and B, but zoning of natural resource use has been done only in A, where shading denotes "total protection" areas and no shading denotes "sustainable use" areas (see the text). The bottom-up replication of the management scheme included the following areas in 2006: Jarauá, Tijuaca, Coraci, and Maraa city; the top-down replication occurred entirely in communities near Fonte Boa city (see the text)

Ribeirinho livelihoods involve various combinations of small-scale agriculture and extraction of natural resource products, mainly fish, game, and timber, which traditionally are traded for purchase of consumer goods from visiting commercial intermediaries (Moran 1984).

The Mamirauá Reserve was created to protect biodiversity through participatory natural resource management. Ribeirinhos inhabiting the reserve are committed to use all natural resources (e.g., fish, forests, soils, etc.) within the reserve sustainably in exchange for exclusive rights of use over them (i.e., people living outside the reserve cannot exploit resources in the reserve). The reserve was zoned into two major areas of "sustainable use" and "preservation"; in the former, local inhabitants are allowed to use natural resources sustainably (key resources have unique rules of use), and in the latter, no use of natural resources is allowed (Fig. 1). This zoning system was key, as várzea floodplains have traditionally been managed as an open access resource, and this has been a major impediment to its conservation (McGrath and others 1993). These regulations were backed by a system of vigilance in which volunteer members of local communities should intercept rule offenders and request that they comply with the management regulations. These and several other guidelines were established in the reserve's management plan in 1996 (Crampton and others 2004). Currently, the Mamirauá Reserve is established under Amazonas State decree 2.411 of July, 1996, and it is managed by the Mamirauá Sustainable Development Institute, which carries out multidisciplinary research and extension activities.

Importance of Fishing and the Pirarucu

Fishing in general, and in particular fishing of the fish pirarucu (*Arapaima* spp.), is a central element of the ribeirinho economy and culture that always is practiced by men (Queiroz and Sardinha 1999). Fishing of pirarucu in Mamirauá might constitute up to 40% of the total fish catch in weight and is the most important economic activity (Queiroz and Sardinha 1999). Fishing of pirarucu is a highly specialized activity: Only about 10% of all fishers in the reserve are specialized in pirarucu, and they produce between 50% and 60% of the total catch of pirarucu (Queiroz and Sardinha 1999). This specialization comes largely from the practice of harpooning the pirarucu at the moment of aerial breathing, although gillnets also are widely used.

The pirarucu have a number of special characteristics, a major one being their big, tasty, and boneless fillets. The pirarucu breathe air obligatorily, coming out to breathe every 5–15 min (Luling 1964), have relatively small home ranges (Castello 2008a), and can grow up to 3 m in length and 200 kg of weight (Queiroz 2000). They become sexually mature at about 3–5 years of age, when they measure about 1.68 m in length (Castello 2007; Queiroz 2000) and spawn under the forested margins of lakes, open lakes, and connecting channels during rising water levels (Fig. 1; Castello 2008b).

Management of Pirarucu in Brazil

Managing pirarucu is very difficult because wild populations are depressed and possibly declining (Castello and Stewart forthcoming), there are little data on wild populations, and governmental management regulations are not followed. The exploitation of pirarucu in Brazil has undergone phases of boom and doom in the last century. In the 19th century, pirarucu were responsible for the most important fishery of the Amazon (Veríssimo 1895, p. 117), but pirarucu landings and the average size of captured individuals started to decrease drastically by the 1950s (Isaac and others 1993). Today, the scarce data available indicate that the pirarucu are overfished in most of the Amazon (Isaac and others 1993; Queiroz and Sardinha 1999), have been extirpated in some regions, and are vulnerable to extinction (Goulding 1980, p. 210). A major issue impeding sustainable management of the pirarucu has been a lack of information on population levels. Conventional mark–recapture methods are prohibitively difficult

due to the costs, labor, and the enormous geographic areas involved, and monitoring of landings is practically impossible because of the decentralized and illegal nature of the trade (Bayley and Petrere 1989).

Government attempts to manage the pirarucu fishery in the Brazilian Amazon have been largely ineffective. The regional environmental agency (IBAMA) implemented a minimum length of catch (1.5 m) and a closed season (December–May; Viana and others 2004), but those were enforced very poorly because of lack of human and financial resources (Bayley and Petrere 1989). The post of IBAMA near the Mamirauá Reserve in Tefé city (Fig. 1) was staffed by just eight agents, was responsible for an area of 251,000 km^2 (about the size of Italy), and did not even possess a boat until 1999, in a region where all transportation is made on boats (Crampton and others 2004). IBAMA banned the pirarucu fishery in the State of Amazonas in 1996 under suspicion of overexploitation (Viana and others 2004), but illegal fishing remained widespread.

Management of Pirarucu in Mamirauá

Initial attempts to manage pirarucu populations in the Mamirauá Reserve also were ineffective. Research done in 1993–1995 showed that only 30% of the harvested pirarucu were longer than the legal length limit, and they were caught irrespective of the closed season (Queiroz and Sardinha 1999). These findings had methodological problems caused by underreporting of mostly undersized and off-season fish; therefore, these findings were "optimistic" at a minimum. Pirarucu populations and fishing practices in the reserve were expected to improve after 1996, when the management plan of the reserve was implemented. However, research done in 1998 found essentially the same findings as those in 1993–1995 (Viana and others 2004). This was critical as a previous study predicted that pirarucu populations would collapse if exploitations rates were maintained (Queiroz and Sardinha 1999). Thus, fishing of pirarucu in the reserve was mostly illegal and threatened pirarucu populations despite the reserve's zoning and vigilance systems.

The vigilance program run by the Mamirauá Institute was partly effective. For one, the program was short of volunteers because of the danger involved. For another, the vigilance program was largely ineffective with respect to locals because local communities have strong kinship networks between families and family-members. Vigilant volunteers often faced the problem of having to sanction relatives or close friends (Gillingham 2001). Additional vigilance and enforcement was done by IBAMA (mostly at regional landing ports) and agents paid by the Mamirauá Institute. However, these also were poorly effective because of the large costs and geographical areas involved and intermittent availability of funding (Crampton and others 2004).

Participatory Research and Management of Pirarucu in Mamirauá

The Mamirauá Institute began in 1998, a new program to sustainable fisheries in the Jarauá area of the reserve, where four communities controlled about 562 km^2 of várzea and about 80 lakes (Fig. 1). Fishers from Jarauá had demonstrated interest in conserving fish resources, and they already had been following some management regulations that were devised by themselves in order to protect local fish stocks. Every year, Jarauá fishers banned the use of gillnets in their area for a whole a month. Their rationale was that fishing with gillnets in August–September (when water levels decline) prevents the fish from migrating out of connecting channels into the lakes, where they are usually caught (Castello 2008a). Jarauá fishers were relatively well organized, had an effective leader, and met regularly to discuss community issues and resolve conflicts; they met mostly among themselves but also with governmental and other organizations such as the Mamirauá Institute (Viana and others 2004).

Research efforts done in 1998 focused on developing a method to count the pirarucu at the moment of aerial breathing. Few fishers were confident that the pirarucu could be counted, and most scientific methods for counting animals [e.g., DISTANCE (Buckland and others 2001)] are based on assumptions that do not apply to the pirarucu. Following the advice of a herpetologist with many years of experience in Mamirauá (R. Da Silveira, Universidade Federal do Amazonas, Manaus, Brazil), two fishers were identified who were amenable to the idea of counting the pirarucu. Together, the two fishers counted the pirarucu in a few lakes using an improvised method; the accuracy of their counts, however, remained to be tested.

The counting method developed by the two fishers was standardized by Castello (2004) through 6 months of close collaborative work with the two fishers. The method established (1) that fishers counted the pirarucu during a period of 20 min, (2) that the counts were done within an area no greater than 2 ha that was established by the fishers themselves, (3) that only pirarucu longer than 1 m were counted, and (4) that counted pirarucu were classified as juveniles (1–1.5 m) or adults (>1.5 m). If the area of a lake was larger than 2 ha, two or more fishers would do the counts simultaneously. If the number of available fishers was insufficient to cover the entire area of the lake doing simultaneous counts, the fisher(s) would do successive counts until the entire area of the lake was covered. In this way, the count method allows for population censuses, not just indexes of abundance, as do most population

assessments. The fishers count the pirarucu by differentiating among surfacing individuals on the basis of subtle visual and acoustical cues; skills needed to count the pirarucu are held only by those fishers very experienced in harpooning (Castello 2004).

In 1999, counts of pirarucu done by fishers from Mamirauá in closed lakes were compared with mark–recapture estimates of abundance for the same populations; the estimates by these two methods were highly correlated ($r = 0.98$; Castello 2004). In 2000, the possibility of training fishers from different regions to count pirarucu was tested. After a short training period, the ability of other fishers to count pirarucu was assessed in a manner similar to that of the fishers from the Mamirauá Reserve. Counts of pirarucu and mark–recapture estimates of abundance again were highly positively correlated, indicating that other fishers also could count the pirarucu, and that, to some extent, the method could be passed from one fisher to another. This method used to count the pirarucu has the advantage of being very cost-effective; it is $\sim$ 200 times faster and less expensive than the mark-recapture method used by Castello (2004).

At the same time that research on pirarucu was being done, extension activities with Jarauá communities focused mostly on improving the organization of the fishers and eliminating commercial intermediaries (Viana and others 2004). It was thought that selling the pirarucu directly to the buyers would increase fishers' profits, thus lowering fishing pressure on fish populations. Thus, technicians of the Mamirauá Institute identified alternative potential buyers, and the informal organization of the fishers was formalized in the form of an Association of Producers. This Association of Producers allowed the fishers to deal with buyers outside the state and required the fishers to commit formally to obeying regional fishing regulations and local decisions made by the association, although fishers were not required to conduct all their commercial transactions through the associations.

With the discovery that fishers could count the pirarucu and with a formal Association of Producers, the Mamirauá Institute negotiated with IBAMA the possibility of legal harvesting of pirarucu. The IBAMA had banned the fishery in the state but had made exception to cases of scientific and experimental nature (Viana and others 2004). This prompted the Mamirauá Institute to implement an experimental management system where counts of pirarucu were done annually, used to determine harvest quotas, and then used to request harvesting permits to IBAMA. The catch was then sold to buyers offering the best prices.

Counts of pirarucu have been done every year from 1999 to today by fishers from Jarauá communities who had their counts validated with mark–recapture assessments (Castello 2004). A group of about eight fishers counted the pirarucu during the dry season, when the pirarucu inhabit mostly the lakes (Castello 2008a), in the entire area under the control of Jarauá communities (Viana and others 2004). From 1999 to 2001, fishers were paid by the Mamirauá Institute for counting pirarucu (it was viewed as research work) and were compensated by their communities in the following years. Technicians of the Mamirauá Institute accompanied the fishers during the counts to avoid possible cheating (e.g., inflating counts to get larger fishing quotas).

The counts done in one dry season were used to determine harvest quotas for the next dry season (i.e., the following year). For the first harvest quota, however, information on counts of pirarucu would become available only a few months after the peak of the fishing season. So, the harvest quota of 1999 was determined based on an estimate of sustainable production of pirarucu in Peru (Viana and others 2004). As it turned out, the harvest quota for the first year was about 30% of the number of adult pirarucu in the Jarauá area the previous year. Because harvesting this proportion of the adult population seems to have allowed the population to recover (see Fig. 2a) while yielding increasing harvest quotas for the fishers, the same rationale was applied in subsequent years. The quotas were determined first through negotiations between the fishers and technicians of the Mamirauá Institute and then through negotiations between the former two and IBAMA. In the first 2 years, the fishers accepted the harvest quotas that the technicians proposed and that they initially considered being too small, only because they were assured by the technicians that the selling prices would be higher than prices of the illegal product (Viana and others 2004).

Obtaining the harvest permits from IBAMA was problematic at first. In 1999, IBAMA officials received extensive documentation on the method used to count the pirarucu and on the management scheme proposed. Negotiations were difficult, but eventually the harvest quota was granted (Viana and others 2004). In 2000, fishers and technicians from the Mamirauá Institute requested a harvest quota greater than in 1999, because the population of pirarucu had increased, but IBAMA officials granted a quota of two-thirds the size of the requested quota. The official technical statement explained that the requested quota was "too much" (Viana and others 2004) and provided no additional justification. In 2002, the counts of pirarucu indicated that the population had increased by about 480% relative to 1999. The fishing quota set by the fishers and technicians of the Mamirauá Institute, which was set as 3 tons in 2000, now had increased to 15 tons (Viana and others 2004). This time, government officials denied granting the harvest quota; the official statement explained that "[local fishers and technicians of the Mamirauá Institute] were proposing weird ideas" (Viana and others 2004). This lack of understanding, and perhaps skepticism, of the management

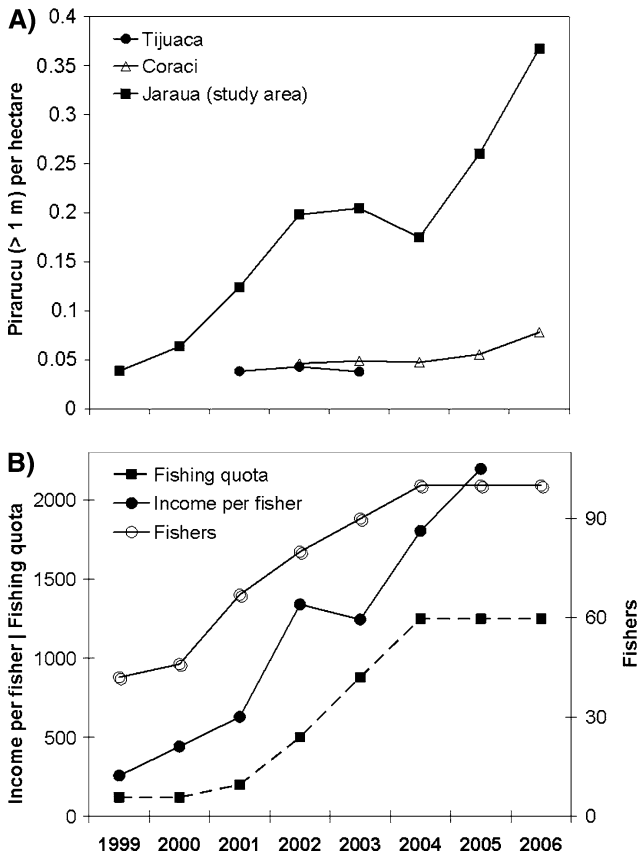

Fig. 2 Major quantitative results achieved by the participatory management scheme for the pirarucu in Jarauá communities at Mamirauá. **a** Trends in pirarucu population in the study area and neighboring areas near or at the Mamirauá Reserve (see Fig. 1), indicating the effectiveness of the management scheme; **b** number of fishers involved in the management scheme in the study area, annual income of the fishers involved in the management scheme, and total fishing quotas harvested in the study area. Data on pirarucu population are from Arantes and others (2006); all other data are from Viana and others (2004, 2007). Data on income per fisher was measured in Reais (Brazilian currency). Data on size of adult stock of pirarucu stem from counts made by local fishers using the method proposed by Castello (2004). The counts were done during the dry season in all lakes and water bodies within the management area that contained pirarucu. Note that the census of year 2004 for the study area is underestimated because the unusual high water levels of that year's dry season allowed the pirarucu to be dispersed rather than concentrated in lakes as in most years (Castello 2008b). Harvest quotas are measured in numbers of pirarucu. The official harvest quota for a given year was established based on the adult stock counted the previous year. See the text for details. Note that the Tijuaca area also is located within the Mamirauá Reserve (Fig. 1) and that additional data for the Tijuaca area are available but were excluded due to their unreliability (Arantes and others 2006)

scheme on the part of government officials motivated technicians of the Mamirauá Institute to invite government officials to travel from the distant state capital (some 600 km away) to visit the fishers, the technicians, and the managed area (Viana and others 2004). The visit occurred, the scheme was appreciated by the officials, and negotiations on the harvest permits with the environmental agency were no longer problematic. The visit to the managed area convinced government officials that fishers actually could count the pirarucu and that the management scheme was sound and already had promoted increases in the population of pirarucu.

Improved Management of Pirarucu in Jarauá

After 8 years of experimentation, the main quantitative results achieved by the management scheme in Jarauá are the following (Fig. 2a, b). (1) The combined population of juveniles and adults of pirarucu increased 9-fold; the adult population of pirarucu increased 23-fold. (2) The harvest quotas increased 10-fold. (3) The number of fishers participating in the management scheme more than doubled. (4) Per capita income of the involved fishers increased 8-fold.

There is convincing reason to believe that the observed increase in pirarucu population is real, as population trends indicated by the counts are followed closely by a conventional index of fish abundance, catch per unit of effort (CPUE). Mean CPUE of pirarucu in Jarauá during the fishing season increased fourfold, from 4.41 kg/fisher/h for years 1995–1997 (Queiroz 2000) to 17.25 kg/fisher/h in 2003 (Maccord and others 2007), and counts of pirarucu increased fivefold, from about 2200 pirarucu in 1999 to about 11,500 in 2003 (Fig. 2a). Moreover, the observed increase in pirarucu population likely was caused by the management scheme, as adjacent and neighboring pirarucu populations have not grown similarly (Fig. 2a). To our knowledge, no environmental factor has affected the pirarucu population in the study area (Castello 2007). However, the impacts of improved management of pirarucu on other fish species is unknown. Fishers have discussed the need to develop management systems for tambaqui (*Colossoma macropomum*), which is a high-value fish species, but the very large home ranges of this species render little utility to community-scale actions.

We suggest that the increase in numbers of fishers involved, half of which are the fishers' wives (who generally do not fish for commercial purposes; Fig 2a, b), reflects increased levels of participation in the management process. The fishers' association had 42 members in 1999, all of whom were men; it possessed 71 men and 29 women members in 2006. This increase has been almost entirely spontaneous, as men and women were interested in the economic benefits of the scheme, such as increased per-capita incomes (Fig. 2a, b).

The main qualitative results achieved by the management scheme in Jarauá are the following: (1) increased engagement of fishers in the management process, (2) implementation of a system to promote participation and sanction offenders, and (3) reduced violations of the rules. All of these results are related to a system of individual

transferable quotas that was developed by the fishers themselves through community meetings to sanction offenders and promote participation and rule compliance. In this system, the leaders of the fishers' association have been given the power to assign harvest quotas on an individual basis based on the behavior of the fishers. All fishers get a "standard quota," but fishers who abuse the rules lose the right to harvest all of the quota (the quota gets smaller), and fishers who contribute to the scheme receive larger quotas. These individual fishing quotas can be negotiated and transferred among the fishers; most women give their quotas to their husbands or sell it to others. As an example, in 2005 the "standard quota" was set as 18 pirarucu, and fishers who counted the pirarucu (a whole month's work) had their quota increased by 5 and fishers caught repeatedly fishing illegally had their quota decreased by 2. The effectiveness of this "kinship-based" approach to sanctioning seems to have improved rule compliance, as there is ample anecdotal evidence indicating that the number of offenses has decreased significantly but not completely (Viana and others 2007). Fishers in the community have a good idea of each other's behavior because they tend to fish in groups, their houses are close to each other, and they all tend to have strong family or friendship ties. Data on rule violations, however, are missing, as Jarauá fishers prefer to deal with sanctioning issues in a private fashion. Moreover, as of today, practically all fishers in Jarauá participate in counting the pirarucu, as they have attended training courses on the methodology and have had the accuracy of their counts assessed by comparison with independent estimates of abundance (Arantes and others 2007).

Replication to Other Communities

From 2000 on, other communities in the study area (Fig. 1) began implementing the management scheme outlined above through "bottom-up" and "top-down" processes. The "bottom-up" replication of the management scheme occurred as fishers of the reserve requested spontaneously the Mamirauá Institute to implement the management scheme in their communities. The number of communities managing the pirarucu under the supervision of the Mamirauá Institute thus increased from 4 in 1999 to 15 in 2005. Two additional sets of communities implemented the management scheme: Tijuaca with seven communities and Coraci with four communities (Fig. 1). The neighboring city of Maraa, which has 10,000 inhabitants (Fig. 1), also implemented the management scheme. More communities probably would be involved if the Mamirauá Institute possessed more human and financial resources. As of today, only Tijuaca communities have not been able to manage the pirarucu effectively, at least not nearly as effective as Jarauá and Coraci communities and Maraa city. Reports of illegal fishing and even of cheating counts of pirarucu in Tijuaca communities abound (Arantes and others 2006), and Tijuaca fishers do not make significant efforts to sanction rule offenders.

The "top-down" replication began in 2004 when two things happened. The State of Amazonas declared that legal harvesting of pirarucu was possible only if populations had been counted, and a government-run institute (Instituto de Desenvolvimento Sustentável de Fonte Boa) implemented the management scheme in 92 communities in areas near Fonte Boa city (Fig. 1). Reports by the Instituto de Fonte Boa claim that pirarucu populations in the area of these 92 communities have increased and that local fishers have benefited economically. However, these claims have been challenged by a report prepared by the Mamirauá Institute in 2005 following requests by IBAMA (Garcez and others 2005). That report presented anecdotal evidence of illegal fishing and emphasized that there is no evidence that fishers' count of pirarucu in Fonte Boa communities are reliable (Arantes and others 2007) or that the pirarucu resource actually is being conserved.

Results and Discussion

Establishing the Missing Principles for Sustainability

Our analysis suggests that integrating fishers in all phases of the pirarucu management scheme was key to establishing sustainability. The development of the participatory management scheme was accompanied not only by a dramatic increase of the pirarucu population together with increasing catches (Fig. 2a, b) but also by the establishment of practically all of Ostrom's (1990) principles for sustainable resource use. Only four of Ostrom's (1990) eight principles were present in Jarauá communities before the management scheme was implemented (see Table 1):

- Principle 1 was present before, as the zoning system of the Mamirauá Reserve defined the boundaries of the resource and its users.
- Principle 3 was present before as community members of Jarauá met on a regular basis to discuss community issues.
- Principle 6 was present before, as the Mamirauá Institute promoted and facilitated interinstitutional meetings among local communities, the Institute itself, and other local and regional organizations such as IBAMA.
- Principle 8 was present before as local communities, the Mamirauá Institute, and IBAMA all shared responsibility for pirarucu management. However, it is noted that pirarucu management was not effective even though this principle was in place because tasks related

to appropriation, provision, monitoring, and enforcement were mostly ineffective.

Now, 8 years after the management scheme was implemented, practically all eight of Ostrom's (1990) principles are in place (Table 1A, B):

- Principle 2 was absent before the management scheme started, as size and season limits were violated, the pirarucu population was overexploited and even was expected to collapse (Queiroz and Sardinha 1999). Principle 2 is present now, as the pirarucu population rebounded several-fold, and a new study suggests that current catch rates in Jarauá likely are sustainable (Castello 2007).
- Principle 4 was absent before, as fishers did not report all of their (illegal) catch to the previous scheme of monitoring fish landings. Principle 4 is present now that fishers themselves count the pirarucu and monitor each other's fishing behavior.
- Principle 5 was absent before, as illegal fishing was widespread among fishers. It is present (although weak) now that sanctioning is done through reductions of the fishing quota;
- Principle 7 was absent before, as pirarucu fishing was banned by state regulation. It is present now that fishers can obtain legal harvest permits from IBAMA.

We suggest that there are at least four reasons why fishers' participation in the pirarucu management scheme promoted the establishment of the four of Ostrom's (1990) missing principles: (1) application of the knowledge and skills of fishers in resource monitoring and management; (2) bridging of knowledge systems among all stakeholders; (3) focus on fishers interested in, and capable of conducting, resource conservation; and (4) management under uncertainty. In what follows, we make the case that these four points can be viewed as means to promote sustainable small-scale fisheries in tropical developing countries. These four points can help direct attention to potentially essential issues necessary for success early in the co-management implementation process (Chuenpagdee and Jentoft 2007). This is most important because the relative importance of small-scale fisheries in developing countries has been increasing, as fisheries in developed countries have been declining and there is great need for alternative managerial approaches.

Application of Fishers' Knowledge and Skills

The pirarucu fishery in Mamirauá shows that applying fishers' knowledge and skills was key to supplement and even supplant available information on, and methodologies related to, stock assessment and management. The counts of pirarucu made by the fishers provided for a more effective stock assessment methodology than monitoring of landings and also enabled the development of an alternative management scheme based on the counts. Applying fishers' knowledge and skills was key to establishing Principles 4 and 2, which are related to monitoring the resource and allowing for sustainable fishing practices, respectively (Table 1). That fishers possess knowledge that is useful for management is not new (Haggan and others 2007; Martin-Smith and others 2004; Poizat and Baran 1997; Silvano and Begossi 2005). However, our case reenforces that notion by showing that some fishers possess, in addition to knowledge, valuable skills. Pirarucu fishers count the pirarucu using both their knowledge about the fish and their ability to perceive subtle cues from surfacing pirarucu. This ability was acquired during years of practical experience and can be explained to another fisher but cannot be passed to another fisher without the same expertise (Castello 2004). Skills such as counting can be incorporated in management only through the active participation of the fishers, because, unlike knowledge, they do not exist without the fisher. However, only about 10% of all fishers in Mamirauá are specialized in pirarucu (Queiroz and Sardinha 1999), and this probably represents the proportion of fishers that have the type of knowledge and skills needed for counting pirarucu. Thus, recognizing "expert"' fishers is probably as important as integrating fishers in management processes. The two fishers who were key to developing the counting method were recommended by a herpetologist with working experience in the area. Davis and Wagner (2004) proposed using systematic approaches such as peer recommendations to identify "experts," and we concur.

Bridging Knowledge Systems

The pirarucu fishery in Mamirauá shows that bridging knowledge systems across all stakeholders is key to developing management schemes that are based on accepted and credible rules. Bridging across knowledge systems in our case study occurred through the counts of pirarucu. Because fishers' counts of pirarucu have been shown to be reliable by a scientific study (Castello 2004), IBAMA officials started granting legal harvest permits for the fishers to exploit the pirarucu, and this was key to establishing the missing Principle 7, which is related to the right of fishers to exploit and manage the pirarucu (Table 1). Moreover, because fishers themselves understand and actually do the counts of pirarucu, fishers readily accept and adhere to the fishing quotas. Fishers might well question or not understand data derived from computer calculations showing the same trends. Bridging knowledge systems is needed when integrating fishers in management

(Berkes and others 2006) because fishers probably belong to ethnic groups (Pauly 1997), have distinct cultural beliefs (e.g., Berkes 1999), or lack formal education (Agrawal and Gupta 2005). Hence, fishers likely have difficulty in communicating with scientists and government officials. This difficulty is compounded by the fact that fishers' knowledge is mostly qualitative, narrative, and local—characteristics that contrast sharply with the scientifically objective information that scientists and managers are used to encountering (Baelde 2007).

The pirarucu fishery in Mamirauá also suggests that individual-to-individual contact can improve understanding among stakeholders. The scientific evidence showing that fishers could count the pirarucu accurately and the simple logic of the management scheme proposed did not fully convince government officials of the validity of management scheme. IBAMA officials only supported the management scheme when they visited the managed area in 2002 and saw, in person, that the fishers can count the pirarucu and that managing the pirarucu based on the counts already had promoted increases in the pirarucu population. As Stanley and Rice (2007) put it, "making fishers full partners… ultimately requires a strategy to enhance communication and build trust" and trust between institutions occurs at the individual level (O'Leary, personal communication). In this sense, it seems that improved participation of local people in decentralized management schemes requires "incentives to promote more interactions between less powerful rural residents and government officials" (Agrawal and Gupta 2005).

Working with Fishers Interested in and Capable of Conducting Resource Conservation

Our case study shows that identifying and working with fishers that are interested in, and have the capacity to conduct, resource conservation is critical to the effectiveness of management schemes. Because fishers in Jarauá have interest in, and the social organization needed to conduct, pirarucu conservation, they have started sanctioning rule offenders, thereby establishing missing Principle 5 (Table 1). Only fishers from Tijuaca communities in the Mamirauá Reserve have implemented the management scheme but not achieved positive results (see Fig. 2a). Tijuaca fishers differ from all others in that they seem to be more heterogeneous; some fishers are interested in conservation, but several others break the rules repeatedly. Identifying fishers' interest and capacity to conduct resource conservation scheme is key because "rational fisheries do not exist if both [fish and fishers] are not well tuned" (Castilla and Defeo 2001) and because it is relatively easy for fishers to fish illegally in tropical developing countries, where enforcement of regulations tends to be poor or nonexistent. Technicians from the Mamirauá Institute sought to identify suitable fishers to manage the pirarucu by assessing both their commitment and the capacity of their social organization to face the challenges of resource management. This was done though formal and informal conversations with the fishers themselves and by consulting with colleagues of the Mamirauá Institute and other organizations who have experience with the fishers. However, the experience with Tijuaca communities suggests the need for reliable methods to identify fishers' interest and capacity to conduct resource conservation. Balazs (1998) and Johannes (1998) have shown that fishers that are responsible in using coastal resources tend to have communities with old traditional roots. Aswani (2005) assessed cultural attitudes with respect to governance and management of marine resources and found that understanding the effectiveness of existing local governance institutions is key to predicting the outcome of introduced management systems.

Management Under Uncertainty

The pirarucu fishery in Mamirauá suggests that management must be done even under conditions of uncertainty. When the technicians from the Mamirauá Institute proposed using the counts of pirarucu to determine harvest quotas and when the harvest quotas were actually determined, no person involved in the scheme could predict the outcome. However, because the management scheme in Mamirauá focused on using all and whatever information was available, the four missing principles in Jarauá are present now. Relatively few studies were done on the pirarucu and its fishery; yet they were sufficient for developing what now probably has become the most effective strategy for the sustainable management of the pirarucu. We wish not to belittle the value of biological or ecological information, but rather to emphasize that effective management is possible under uncertainty as long as uncertainty is recognized (Ludwig and others 1993).

Toward Conservation of Tropical Small-Scale Fisheries

The pirarucu fishery in Mamirauá shows that models of sustainable tropical small-scale fisheries can be developed in fishers if are integrated in management by matching and assigning the responsibilities of each stakeholder group with the appropriate levels of capacity and scale. The Mamirauá Institute supplanted IBAMA's role, thus overcoming IBAMA's problem of lack of human and financial resources to do its job effectively. IBAMA played a key role in passing legislation relevant for encouraging the fishers to follow sustainable fishing practices. The fishers helped establish, in their communities, management

systems that supplement IBAMA's previous roles as a centralized management organization. The "top-down" replication of the management scheme in 92 communities near Fonte Boa city lacks mechanisms to assess the validity of the counts made by the fishers as well as to monitor and enforce compliance with the regulations. However, applying the conventional premise that resource users must be accountable to government agencies would determine that pirarucu populations remain overexploited in a state of virtual no-management. What is preferred, no-management or possible mismanagement? Does either option matter when pirarucu populations already are overexploited? We believe that the involvement of these communities in management is a significant step toward sustainable fisheries that should continue to be promoted, although certainly there are reasons for concern that must be studied and addressed in the near future.

We believe that our findings can help develop urgently needed alternative approaches for small-scale fisheries management in the tropical world (Castello 2008c; Castello and others 2007; Castilla and Defeo 2001; Orenzans and others 2005; Pauly and others 1989). A brief inspection of Ostrom's principles (Table 1) suggests that small-scale fisheries worldwide tend to lack five out of the eight principles. Principle 1 generally is undermined by the open-access nature of many fisheries (Gordon 1954). Principles 4, 5, 6, and 8 are undermined to some extent by the lack of fisheries agencies and attention from policy makers and managers (Berkes and others 2001; Mahon 1997; Pauly 1997). We have shown that fishers can be extremely valuable in promoting conservation in small-scale fisheries, and we have suggested four ways of integrating fishers in management processes more effectively.

Acknowledgments We dedicate this study to the memory of Seu Antonio Martins, a leader of Mamirauá fishers who is missed by all who knew him. This study would not have been possible without years of friendship, close collaboration, and uncountable discussions with Mamirauá fishers. We thank J. Gibbs, T. O. C. Castello, C. Franco, D. Stewart, C. Hall, F. Berkes, and T. Buchholz for comments on various versions of this manuscript. Two of the three anonymous reviewers (including Renato Silvano) provided valuable constructive comments. Funding was provided by the Sociedade Civil Mamirauá and the Conselho Nacional de Pesquisa (Brazil), the Department for International Development (England), and the Wildlife Conservation Society, and the Overbrook Foundation (United States).

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