

Assessing the impact of conservation agreements on threatened fish species: a case study in the Colombian Amazon

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Abstract Although biodiversity has value for the global community, biodiversity protection often imposes costs on local communities. Correcting this misalignment requires appropriate local incentives. Conservation agreements (i.e. negotiated transactions in which conservation investors finance social benefits in return for conservation actions by communities) are a form of direct incentive. The results of this approach depend on effective monitoring of ecological and socio-economic impacts to verify that environmental and development objectives are met. Monitoring is also needed to verify that parties to the agreements comply with their commitments. Ecological monitoring results for agreements between Conservation International and communities in the Colombian Amazon show positive conservation impacts. These agreements are designed to protect forest areas and two threatened fish species that are important to local livelihoods and have high commercial value. We show how effective monitoring is essential for identifying long-term sustainability options. Lessons learned from this project inform reflection on emerging frameworks for scaling up the approach to the national level.

Keywords Arowana, Colombia, conservation agreements, incentives, indigenous communities, monitoring, pirarucú

Introduction

Biodiversity has value for the global community, but conservation of habitats and species can involve non-trivial costs for local communities in developing countries (Balmford et al., 2002). These costs can preclude the behaviour change needed to achieve conservation objectives, raising the need for incentives to help communities overcome the cost of conservation. Conservation International, through its Conservation Stewards Program, uses conservation agreements to create such incentives in more than 15 countries, to protect 1.5 million ha of habitat and improve the livelihoods of 35,000 people. These initiatives have

also been scaled up to regional and national programmes, conserving an additional 1.7 million ha and benefiting more than 240,000 people. The model offers direct incentives, with conservation investors providing a negotiated benefit package in return for conservation actions by communities (Simpson & Sedjo, 1996; Ferraro, 2001; Ferraro & Kiss, 2002; Niesten et al., 2010). Thus, the agreements link funders (governments, bilateral agencies, companies, foundations, individuals, etc.) to resource owners whose decisions influence conservation outcomes (Milne & Niesten, 2009).

Direct incentives offered under conservation agreements can take the form of cash disbursement to individuals and/or community funds, thereby converging with direct payments for conservation (Ferraro & Kiss, 2002; Milne & Niesten, 2009; Clements et al., 2013). Like such approaches, the efficacy of agreements hinges on verified compliance with commitments. Conservation agreements also share this quid pro quo character with payments for ecosystem services (Wunder, 2005, 2007; Engel et al., 2008). Conservation agreements are a means to make a wide variety of interventions (payments for ecosystem services, co-management of protected areas, environmental offsets, and others) tangible and attractive for communities.

Here we describe the conservation agreement model and its application in Colombia's Amazon region to conserve freshwater fish species. To demonstrate the impacts of these agreements, we summarize fish population trends revealed through 8 years of monitoring, noting the challenge of linking interventions to outcomes (Baylis et al., 2016). We show how ecological monitoring results are shaping plans for sustainable extraction and we conclude by noting implications for scaling up.

The conservation agreement model

The conservation agreement model consists of four phases: feasibility analysis; community engagement; agreement design and negotiation with resource users; and implementation (CSP, 2016). The feasibility analysis informs implementers whether an agreement may be suitable for a given site. If so, the implementer approaches the resource users to introduce the model and gauge community interest in developing an agreement. If resource users explicitly express a desire to proceed, joint design of the conservation agreement begins.

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Received 21 September 2016. Revision requested 9 November 2016.

Accepted 2 June 2017. First published online 9 October 2017.

The agreement specifies rights and responsibilities of the parties involved, conservation commitments of resource users, benefits provided by the implementer, and penalties for non-compliance (CSP, 2016), resembling payment for ecosystem services as defined in Wunder (2005). Most agreements involve two parties, with one undertaking conservation actions and the other providing benefits and technical support for those actions, but other parties, such as government, may be involved. Community commitments in the agreement are based on the conservation objective; they can include direct behaviour change, such as spatial restraints on shifting cultivation or desisting from illegal hunting or fishing, and/or actions to reduce external pressure, such as patrolling to deter poachers. Benefit packages are designed to address the opportunity cost of conservation: the value of foregone resource use, such as income lost by not expanding crop fields, plus the cost of conservation actions such as time spent patrolling. Benefits can include cash payments to individuals, often as wages for patrolling, and/or investments that provide group benefits, such as small-scale irrigation infrastructure.

A key feature of conservation agreements is that benefits depend on compliance with commitments (Milne & Niesten, 2009). Graduated penalties are defined jointly by implementers and communities as part of agreement design. Sanctions usually start with an admonishment letter requesting corrective actions. If non-compliance persists, the benefit package is reduced temporarily, with restoration of full benefits once needed actions are taken. Finally, in the event of continuous breaches, implementers terminate the agreement and then must decide whether to pursue an alternative strategy, such as intensified law enforcement, or redirect scarce conservation funds to initiatives elsewhere.

Often, an initial agreement is signed for 1 year; if it works well the parties renegotiate and renew for another year. After 3–5 years, implementers explore sustainable financing options for a long-term agreement. Options include trust funds, payments for ecosystem services (e.g. carbon sequestration, watershed protection), and private sector partnerships (e.g. social and environmental offsets, or green enterprises). Some countries offer scope for government programmes that support conservation and poverty alleviation through conservation agreements, as in Ecuador's Programa Socio Bosque (de Koning et al., 2011) or the Programa de Incentivos por Conservación, Manejo Integral y Servicios de Bosque in the Department of Pando, Bolivia (Espinoza et al., 2015). Sustainability also involves improved local governance capacity to reduce reliance on technical support. Once sustainable finance is in place, a long-term agreement can be signed.

Monitoring conservation agreements

Monitoring is essential to verify that conservation agreements achieve environmental and development objectives.

Monitoring is also needed to verify agreement compliance, and the presence of meaningful monitoring can itself be a driver of behaviour change (Sommerville et al., 2010). The model's emphasis on monitoring responds to increasing calls for more rigorous impact evaluation in the conservation arena (Kleiman et al., 2000; Ferraro & Pattanayak, 2006; Fisher et al., 2014; Baylis et al., 2016). A well-designed conservation agreement includes attention to evaluation such that monitoring results facilitate clear attribution of impacts to interventions (Ferraro & Hanauer, 2014). This provides confidence that funds are well spent, and is essential for convincing funding sources and policy makers of the value of scaling up the approach.

Monitoring compliance with conservation commitments is often performed by the implementers. Typically implementers can observe compliance directly, as they provide technical assistance and project follow-up. In addition, implementers should devise systems that encourage community members to report infractions by others, and ensure that sanctions are applied. Regular reviews of the agreement by the implementers and communities permit examination of accomplishments and analysis of why some conservation commitments may go unfulfilled.

To ensure objectivity, biodiversity monitoring is led usually by third parties other than the implementer or resource users. Each agreement defines biodiversity baselines and measurable conservation goals, such as number of hectares conserved or species populations maintained/increased, and annual monitoring tracks progress on these goals. Monitoring results are used to fine-tune agreement terms over time. Involving resource users in biodiversity monitoring efforts has helped empower and engage communities in several agreement sites (e.g. Cambodia, China, Colombia and Guatemala).

Whenever possible, socio-economic monitoring is also conducted by third parties. As with biodiversity monitoring, a socio-economic baseline established in the first year of the agreement is followed by annual monitoring. The purpose is to understand changing socio-economic conditions of resource users and track community perceptions about the agreement and the benefits provided, as these will influence compliance and agreement robustness. With an eye to longer-term sustainable resource management, socio-economic monitoring also considers institutional development and governance capacity. Finally, socio-economic monitoring informs renegotiations to ensure that benefits respond to community priorities and that resource users are satisfied with the design and implementation of the agreement.

Monitoring of compliance is distinct from monitoring of ecological and socio-economic impacts, although ideally verified compliance can be linked to measurable positive impacts. However, the credibility of asserted links must be examined carefully during project evaluation. A strong record

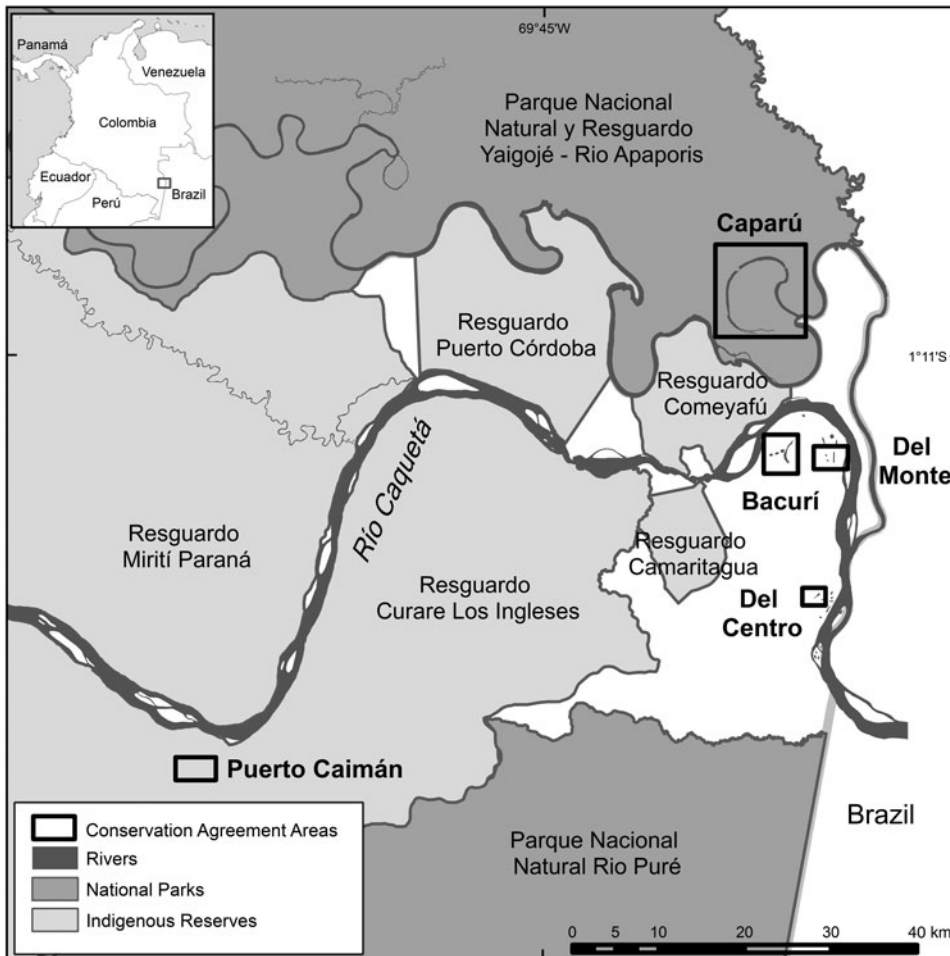


FIG. 1 Location of the sites in La Pedrera, Amazonas, Colombia, where Conservation International established conservation agreements with local communities to protect forest areas and two threatened fish species, the pirarucú *Arapaima gigas* and the arowana *Osteoglossum bicirrhosum*.

of community compliance with an agreement may not yield desired outcomes if, for example, impacts of climate change or intense pressure from outsiders overwhelm local management actions. Likewise, care must be taken to ensure that positive impacts can be attributed legitimately to behaviour change brought about by a conservation agreement.

Conservation agreements in the Colombian Amazon

In 1998 Conservation International's Colombia programme began working in the *corregimiento* of La Pedrera, in the Amazonas Department bordering Brazil (Colombia is divided administratively into Departments, which comprise municipalities and *corregimientos*; these in turn may be divided into districts called *veredas*). During 2002–2004 the programme conducted a participatory environmental assessment of the Lower Caqueta river basin, with three Indigenous Reserves and two *veredas*. Building on previous ecological research, the assessment informed management plans for legally recognized community territories in 2005. While preparing these plans, communities identified El Francisco Creek and the lakes of Puerto Caimán, Bacurí,

Del Monte and Taraira as priorities for local well-being (Fig. 1). By 2008 the management plans included resource-use rules and designated conservation areas, but the communities lacked the means to carry out management activities. Outsiders continued to fish pirarucú *Arapaima gigas* and silver arowana *Osteoglossum bicirrhosum* within the conservation areas, using destructive methods and harvesting fish below the legal minimum catch-size; local fishers, seeing the rules violated with impunity, followed suit.

The arowana exhibits paternal mouth brooding, in which the male cares for the eggs and fry. This species congregates in small schools, sought by fishers to extract males carrying fry in their mouths. The fry are transported to Bogotá for export as ornamental fish to Europe, Asia and the United States. In Colombia an estimated 195,000–1,150,000 fingerlings are sold per year (Mancera-Rodríguez & Álvarez-León, 2008), and this market pressure has caused local extinctions in several areas of the Amazon (Duque et al., 2008; Proterra, 2012). The pirarucú is the world's second-largest freshwater fish, with records of individuals exceeding 3 m in length and 200 kg in weight. Like the arowana, it is an oral incubator. The pirarucú has also been driven to local extinction in

several areas of the Putumayo basin and the Colombian Amazon as a result of its high commercial value, especially in sales to restaurants, and has been listed in Appendix II of CITES (2017) since 1992 (Duque et al., 2008; Proterra, 2012; Fishbase, 2015; IUCN, 2016). Although *Arapaima gigas* is categorized as Data Deficient on the IUCN Red List (World Conservation Monitoring Centre, 1996) and the global status of *Osteoglossum bicirrhosum* has not been evaluated, at the national level in Colombia both are listed as Vulnerable based on IUCN criteria (Ministry of Environment, Housing and Territorial Development, 2010).

Both arowana and pirarucú live and breed in lakes in the project area but migrate during the rainy season when the lakes and rivers are connected (Duque et al., 2008; Moreno-Arias & Moreno-Arias, 2010; López-López et al., 2011; Proterra, 2012). Migration can complicate monitoring and species-focused incentive arrangements for conservation in marine or aquatic systems (Begossi et al., 2011; Bladon et al., 2016), but the agreements in the Colombian Amazon benefit from a focus on lakes that serve as primary breeding areas. By 2008 communities were consistently reporting increasing scarcity of fish in lakes, rivers and streams as a result of over-exploitation by local fishers and others from surrounding communities, La Pedrera, and Brazil. Destructive fishing methods (e.g. fine-mesh netting and poison) also affected other species, such as black caimans *Melanosuchus niger*, giant otters *Pteronura brasiliensis*, giant river turtles *Podocnemis expansa* and c. 20 other fish species that are important sources of protein for local communities.

During 2008–2009, Conservation International established conservation agreements to conserve pirarucú, arowana and other species with seven communities (c. 500 people) in the three Indigenous Reserves and two *veredas*. The communities were selected based on proximity to key lakes and creeks and desire to improve implementation of territorial management plans. The agreements seek to conserve 193,870 ha of freshwater ecosystems and surrounding forest, by providing incentives to offset the opportunity cost of foregoing destructive fishing practices and undertaking activities to enforce regulations and conservation areas defined in management plans.

The agreements were signed by leaders in each community following extensive consultations with all members, witnessed by representatives from indigenous peoples' organizations linked to the Reserves. Each community also had a natural resource committee that was instrumental firstly in developing the management plans, and then in designing conservation agreement terms focused on capacity to implement the plans. Capacity-building of the committees themselves was also included as an agreement benefit.

The communities committed to stop fishing pirarucú and arowana in protected lakes and creeks, forbid fishing during the spawning season, use only artisanal fishing gear, establish fishing quotas for other species, and

participate in surveillance activities to prevent outsiders from fishing in conservation areas. Restrictions on fishing by community members reflect voluntary commitments to uphold self-imposed regulations in the management plans, and vigilance efforts against outsiders reinforce indigenous rights to control territorial access. Patrolling teams consist of three community rangers from different families. Each patrolling campaign lasts 30 days. If outsiders (or insiders) are found fishing for pirarucú or arowana in protected lakes or creeks, patrollers inform the natural resource committee of their Indigenous Reserve or *vereda*, which then reports the incident to local police and environmental authorities. Patrollers also participate in pirarucú and arowana monitoring, such that the methodology we describe below incorporates their knowledge.

In exchange for these efforts, community rangers are paid the equivalent of the prevailing wage rate. Patrol team members rotate monthly to ensure that nearly every family in each community can participate. However, community rangers do not have the authority to arrest and detain people and do not carry weapons, so they require support from police and military to enforce restrictions against outsiders.

The benefit package includes funds for natural resource committees, to ensure they have the means to report problems to authorities. Additional benefits of the agreements include investment in community leadership and governance, such as training in administration, conflict resolution and planning. Communities also enjoy further advantages beyond the direct benefits, as lake protection supports a range of fish species that are vital to food security, and community patrolling also strengthens territorial rights. The value of this last consideration is further enhanced in the Indigenous Reserves, where lakes protected by agreements are also sacred sites.

The agreements explicitly define graduated sanctions to be applied in case of non-compliance. Each community defined internal sanctions for members who breach the agreements, based on the severity of the infraction. Minor infractions (e.g. using project equipment for non-project travel) result in a warning initially, and after a second offence transgressors are penalized by a 10% wage reduction. If non-compliance persists, the offender is suspended from the project for 6 months. Serious infractions (e.g. shirking on patrolling duties) result in a 20% wage reduction. A second offence leads to a 6-month suspension from the project. Sanctions for very serious infractions (e.g. taking pirarucú and arowana from protected lakes) include expelling the transgressor from the project for 1 year.

Conservation International applies external sanctions only when communities do not apply internal penalties. A community that does not comply with its commitments loses 10% of its annual benefit package; these funds can be recovered if the breach is resolved. Upon a second breach, a community forfeits

TABLE 1 Project context for conservation agreements between Conservation International and communities in the Colombian Amazon (Fig. 1), to protect forest areas and two threatened fish species, the pirarucú *Arapaima gigas* and the arowana *Osteoglossum bicirrhosum*, including details of two control sites.

Lake	Species	Conservation agreement	Community	Indigenous Reserve or <i>vereda</i>
Bacurí (intervention site)	Pirarucú & arowana	Yes	Madroño	Madroño (<i>vereda</i>)
Taraira (intervention site)	Pirarucú	Yes	Puerto Ñumi Bocas del Taraira (withdrew in 2009)	Yaigojé–Apaporis (Indigenous Reserve)
Puerto Caimán (intervention site)	Arowana	Yes	Borikada Curare	Curare–Los Ingleses (Indigenous Reserve)
Del Monte (control site)	Pirarucú & arowana	No	Conservation agreement terminated in 2013	Villa Marcela (<i>vereda</i>)
El Centro (control site)	Pirarucú & arowana	No	Conservation agreement terminated in 2013	Villa Marcela (<i>vereda</i>)

20% of the annual payment, and the agreement is terminated after a third breach. The communities can also penalize the implementer for failure to deliver technical support or benefits on time: on the first occasion Conservation International must pay USD 90 to the community fund, the second time USD 180, and the third time USD 270. Sanctions are decided on and applied during monthly meetings between the communities and Conservation International.

The initial agreements involved seven communities distributed among three Indigenous Reserves and two *veredas*: Borikada and Curare (Curare–Los Ingleses Indigenous Reserve), Camaritagua (Camaritagua Indigenous Reserve), Puerto Ñumi and Bocas del Taraira (Yaigojé–Apaporis Indigenous Reserve), and the *veredas* of Madroño and Villa Marcela. After the first year, Bocas del Taraira withdrew from the programme to avoid conflict with a neighbouring community where an influential fisher continued to ignore harvest restrictions in Taraira Lake. In 2013 Conservation International terminated the agreement with Villa Marcela because of persistent harvesting and selling of pirarucú, despite several warnings and community meetings. Table 1 summarizes the communities and lakes covered by the project, as well as lakes no longer covered by the project but examined for purposes of comparison.

Monitoring impacts of the Colombian conservation agreements

Impact monitoring of the agreements sought to examine three principal issues. Firstly, are the agreements producing the desired biodiversity conservation outcomes, as indicated by trends in pirarucú and arowana populations? Secondly, are the agreements improving the lives of people in the communities, as reflected in socio-economic indicators? Thirdly, are the outcomes sustainable, as captured by metrics relating to community resilience to ecological and economic shocks? Here we focus on ecological results to examine whether

conservation objectives are being achieved, and to assess long-term sustainable resource use options.

The National University of Colombia, through its Amazonian Research Institute, and Conservation International developed the initial ecological monitoring protocol, informed by community knowledge of the ecosystems. The biodiversity baseline was established in 2008, focusing on the lakes and excluding El Francisco Creek, as there is no robust monitoring framework for measuring pirarucú or arowana in rivers. Annual third-party monitoring was then conducted by the University of Antioquia, focused on the lakes of Puerto Caimán (Curare–Los Ingleses), Bacurí (Madroño) and Taraira (Yaigojé–Apaporis). In 2013, river levels were unusually high; continuous connectivity between rivers and lakes precludes reliable counts, so monitoring was foregone at all sites that year. In 2015 the monitoring effort also examined Del Monte and El Centro lakes (Villa Marcela), not covered by agreements, for comparison with lakes covered by the project. (Although the Villa Marcela agreement was terminated in 2013, the community consented to monitoring in Del Monte in 2014, and both Del Monte and El Centro in 2015.) Since 2013 Del Monte and El Centro lakes have served as control sites, as per impact evaluation practice (Ferraro & Hanauer, 2014). Ideally project monitoring would have incorporated control sites from the outset, and strictly speaking the way the two non-project lakes came to be included does not conform to best practice for randomized controls (Ferraro & Pattanayak, 2006). However, the impracticality of ideal monitoring and evaluation scenarios is well known (Baylis et al., 2016). Given the realities of implementing conservation in practice, treating Del Monte and El Centro as comparison sites in a natural quasi-experiment illustrates a practical approach that permits inferences regarding project impacts.

The monitoring team, with technical support from the Sinchi Institute and the University of Antioquia, adapted the methodology developed by Castello (2001, 2004) for monitoring pirarucú, which consists of counting individuals

TABLE 2 Population trends of pirarucú in four lakes in the project area in the Colombian Amazon (Fig. 1) during 2009–2015.

Year	Intervention sites						Control sites (as of 2013)					
	Bacurí			Taraira			El Centro			Del Monte		
	Juveniles	Adults	Total	Juveniles	Adults	Total	Juveniles	Adults	Total	Juveniles	Adults	Total
2009	5	6	11	148	130	278	12	9	21	23	18	41
2010	28	4	32	140	151	291	62	26	88	80	33	113
2011	32	8	40	153	136	289	19	12	31	59	25	84
2012	119	23	142	196	163	359	60	30	90	105	46	151
2013	No monitoring											
2014	72	38	110	285	306	591	No monitoring			96	34	130
2015	161	38	199	415	406	821	48	16	64	227	44	271

TABLE 3 Population trends of arowana in four lakes in the project area in the Colombian Amazon (Fig. 1) during 2010–2015.

Year	Intervention sites						Control sites (as of 2013)					
	Puerto Caimán			Bacurí			El Centro			Del Monte		
	Juveniles	Adults	Total	Juveniles	Adults	Total	Juveniles	Adults	Total	Juveniles	Adults	Total
2010	21	32	53	0	4	4	13	22	35	3	21	24
2011	17	14	31	9	1	10	11	1	12	13	6	19
2012	33	19	52	15	3	18	33	3	36	8	9	17
2013	No monitoring											
2014	21	16	37	17	5	22	No monitoring					
2015	3	96	99	91	19	110	0	0	0	2	0	2

as they surface to breathe. Trained community members observe lake surfaces from canoes 100 m apart, and count the number of pirarucú surfacing to breathe in front of them in 30-minute intervals. As adult pirarucú surface every 15–20 minutes, the monitors must count the number of sightings and judge whether they have previously counted the same individual. Juvenile pirarucú are counted only during the first 20 minutes, as they breathe more frequently than the adults. The result is a count of the total population in a lake, but the margin of error remains to be determined by further research. Castello (2004) found that the results from this methodology are closely correlated (coefficient of 0.98) with total population estimates based on extrapolation from individual tagging and recapture records.

The initial monitoring approach for arowana was the same as that for pirarucú, but this proved unsuitable, as arowana are known to swim rapidly in schools near the surface at the lake periphery. This can easily lead to double-counting, and counts can differ by observer, depending on monitoring skills (Moreno-Arias & Moreno-Arias, 2010). The methodology used since 2011 is based on the only documented arowana monitoring experience in the Amazon basin, in Pacaya-Samiria in Peru (Bodmer et al., 2006). Initially the new approach involved community members in canoes surveying lake edges during moonless nights. The monitors illuminated the water on the lake edge and counted the schools, recording numbers of adults and juveniles in each school (López-López et al., 2011). As of 2014, based on reports

from community members that substantial numbers of arowana congregated in the middle of the lakes, the monitoring frame was extended to central lake areas.

Results from monitoring of pirarucú populations show clearly positive trends in the intervention sites (Table 2). The estimated population of pirarucú has increased substantially in Bacurí and Taraira, the two lakes protected continuously since 2008, from 11 to 199 individuals and 278 to 821 individuals, respectively (Taraira Lake is protected under the agreement with Puerto Ñumi even though the Bocas de Taraira community withdrew from the agreement in 2009). Even in Del Monte, where the agreement ended in 2013, the number of juveniles showed a substantial increase in 2015. In contrast, the population in El Centro appears to be stagnating, at best, and may be in decline, probably because it is most vulnerable to illegal fishing because of its location near the border with Brazil.

Similarly, the results of arowana monitoring indicate positive trends in the protected lakes, with pronounced increases in estimated populations from 2014 to 2015 in Puerto Caimán and Bacurí (Table 3). In the lakes of El Centro and Del Monte, where agreements were discontinued in 2013, arowana populations have crashed, consistent with observations of intensive harvesting pressure. Combined with the figures for pirarucú noted above, these trends suggest that incentives provided to communities under conservation agreements helped improve protection and management of key fish species in the project sites.

Tables 2 and 3 suggest different dynamics in the Del Monte and El Centro control sites; without intervention the pirarucú population is declining in El Centro but increasing in Del Monte, whereas arowana populations have crashed at both sites. Geography is the key factor: El Centro is in a sparsely inhabited area that is readily accessible to illegal fishers from Brazil as well as Colombia. Routes to Del Monte pass through inhabited areas and near a national forest reserve, resulting in a greater likelihood of fishers being seen and reported to authorities. Therefore El Centro is subject to greater pressure. Moreover, Del Monte is near other pirarucú habitat, and this species is known to migrate between floodplain habitats, especially during periods with high water levels (Fernandez, 1997; Arantes et al., 2013). Thus, the Del Monte population probably benefits from enhanced protection at Bacurí through both vigilance and law enforcement in the general area as well as biological spillover. Arowana populations crashed at both sites because low initial levels made them particularly vulnerable to any resumption of harvesting.

These monitoring data warrant some caution. Community monitoring raises questions about skills and accuracy, and about possible motivations to overstate positive project outcomes. Guidance and supervision from third-party university experts mitigates these risks. However, impact evaluation with respect to freshwater fish species raises various technical complications, including mobility of the resource, time lags between intervention and observable impact, and the role of confounding factors such as climatic variation, disease, and predator population dynamics (Reid et al., 2013; Adams et al., 2015). Therefore, relationships between conservation actions as verified by compliance monitoring, observed numbers based on ecological impact monitoring, and actual population remain subject to further research and refinement.

Nevertheless, despite methodological challenges, the results indicate that extreme population declines reported by communities prior to 2008 have been replaced by increasing trends in protected lakes. Contrasted with local extinctions observed elsewhere in the Putumayo basin and the Colombian Amazon, these results strongly suggest that arowana and pirarucú numbers are increasing as a result of the conservation agreements. Monthly community reports also note increasing presence of other species, particularly river turtles and giant otters.

Sustainable extraction

Increases in arowana and pirarucú populations motivated an analysis of the potential for sustainable extraction. Sustainable extraction rates depend on abundance, particularly of mature individuals larger than the minimum legal size for capture: 70 cm for arowana and 150 cm for pirarucú in Colombia (Gómez et al., 2013). Experience in Brazil's Mamirauá Sustainable Reserve and Peru's Pacaya-

Samiria Reserve suggests that extraction rates of 5–10% of adult individuals in a population of pirarucú may be viable (Viana et al., 2007; Gómez et al., 2013).

No defined methodology exists for estimating sustainable extraction rates of arowana fry. For this analysis we assumed the same rates as for pirarucú, recognizing that this may not reflect the actual potential for fry extraction, compounded by uncertainties regarding the methodology for counting arowana. Population figures reported in Table 3, assuming extraction rates of 5–10% for fry, suggest that Puerto Caimán cannot be harvested, whereas Bacurí could yield 4–9 individuals. Based on these results, harvesting arowana fry in the protected lakes is inadvisable, given the low numbers as well as year-on-year variability. Although arowana population trends in intervention sites appear to be positive, the populations have yet to recover from 2 decades of intensive harvesting.

Prospects for sustainable harvesting appear to be more promising for pirarucú, particularly given the greater confidence in the methodology for monitoring population trends. Assuming a 5–10% extraction rate for 2015 populations (Table 2), Bacurí could yield 2–4 mature adults, and Taraira 20–40 mature adults. Gomes (2012) offers further guidance on determining sustainable extraction rates for pirarucú based on population densities in 58 lakes in Mamirauá (Brazil), with density ranges characterized as very low (0.04–1.09 individuals per ha), low (1.21–3.53 individuals per ha), medium (3.78–8.41 individuals per ha) and high (9.39–45.66 individuals per ha). As numerous factors affect population density, including habitat characteristics, life cycles, and intensity of flooding pulses, Gomes (2012) posits that sustainable harvesting requires at least medium density.

Densities of pirarucú in the lakes monitored by the conservation agreement project in the Colombian Amazon are in Table 4. The population density is much lower in Taraira than in other sites because the lake is 40–64 times larger in size, so even with a much larger population the density remains low. Only two lakes had a high population density, in only 1 year: Bacurí and Del Monte in 2015. Medium population density was recorded consistently in Del Monte, and in several years in Bacurí and El Centro, but the trends are not monotonically increasing. The population densities (Table 4) suggest that harvesting pirarucú in the protected lakes would be premature.

A conservative option is to defer harvesting until densities have stabilized at high levels. A second measure to consider is working with community members to identify management zones within the lakes, such that localized population densities can inform harvesting decisions while protection of breeding areas is strengthened (Begossi et al., 2011; Arlinghaus et al., 2016). For instance, shallow portions of lakes or areas close to concentrations of predators are likely to have lower densities, and including them in density

TABLE 4 Population densities (individuals per ha) of pirarucú in four lakes in the project area in the Colombian Amazon (Fig. 1) during 2009–2015.

	Intervention sites		Control sites (as of 2013)	
	Bacurí	Taraira	El Centro	Del Monte
2009	0.6	0.4	1.8	4.0 ¹
2010	1.5	0.3	5.3 ¹	4.9 ¹
2011	2.1	0.4	2.7	5.2 ¹
2012	7.4 ¹	0.5	7.7 ¹	7.4 ¹
2013	No monitoring			
2014	5.7 ¹	0.8	No monitoring	8 ¹
2015	10.4 ²	1.09	5.5 ¹	16.7 ²

¹Medium density

²High density

averaged over the entire lake may understate the health of the population. Other potential sustainable management measures include prohibiting harvesting during breeding periods and setting an appropriate minimum catch size to ensure that individuals breed at least once before capture (Castello, 2001, 2004; Gómez et al., 2013; Arlinghaus et al., 2016).

Discussion

The Colombia agreements seek to strengthen community resource governance, promoting self-determination while enhancing the overall context for socio-economic development. With respect to biodiversity objectives, key aspects of governance relate to respecting management rules and protecting resources against outside pressures. To monitor effectiveness of agreements, periodic assessments are conducted with the resource users. The Colombia project team participates in biannual community assemblies to review compliance. The team also participates frequently in discussions in the Maloca (ancestral long house used for community meetings by Amazonian indigenous groups, particularly in Colombia and Brazil), where people feel more comfortable speaking candidly than in formal household interviews. These interactions have also reinforced social control mechanisms, as people are aware that non-compliance could jeopardize the agreements. Together, increasing governance capacity and social pressure reflect institutional development that facilitates common property management of what was previously an open access resource (Agrawal, 2001; Ostrom, 2005). The incentives provided under the conservation agreements can be viewed as a way to overcome financial and other hurdles that previously prevented such institutional development.

Frequent communication between implementers and resource users and extensive participation of communities in ecological monitoring efforts mean that people are aware of the population trends of pirarucú and arowana.

As they see these populations recovering, community desire to resume harvesting of these economically important species is increasing. Therefore, long-term conservation impact will require continued vigilance, strong social management structures, and sustainable harvesting regimes based on evidence-based determination of viable extraction rates (Begossi et al., 2011; Arlinghaus et al., 2016).

Despite increasing numbers of arowana and pirarucú, sustainable harvesting does not yet appear to be viable. However, orienting monitoring, analysis and discussions with communities around determining sustainable harvesting rates facilitates definition of shared goals on population targets and eventual harvest management regimes. A critical condition for sustainable extraction of arowana will be overcoming the challenges to measuring population status. Moreover, monitoring methods for both species must respond adequately to other factors that can influence fish populations (e.g. climate change), to demonstrate the link between agreement compliance and conservation outcomes (Ficke et al., 2007; Adams et al., 2015; Baylis et al., 2016). Sustainable extraction will also require effective vigilance activities and compliance monitoring, given the risks that community members may neglect harvest restrictions or that outsiders may take advantage of opportunities created by opening of lakes to fishing activities. This need highlights the importance of socio-economic monitoring that captures increase in community governance capacity, including capacity to conduct compliance monitoring (Agrawal, 2001; Ostrom, 2005; Cronkleton et al., 2011), as a precondition for sustainable harvesting.

Conservation agreements are often part of a larger strategy. In the Colombian Amazon, the agreements will not succeed without support from local authorities. Community rangers can inform outsiders that pirarucú and arowana are off limits, but they do not have the legal authority to apprehend transgressors or confiscate fishing gear, and doing so would put their lives at risk. Therefore, community patrols must be reinforced by support from Colombian authorities, including the environmental police. One option being explored is to secure additional financial and policy support from the regional environmental authority, CorpoAmazonia, to continue implementing the current agreements and expand the initiative to other communities facing similar challenges.

Expanded use of conservation agreements with support from a government agency would require monitoring of compliance and impacts on a larger scale. Monitoring frameworks must be adapted to the scale of implementation, and larger scales involve simplification and reliance on remote sensing technologies at the expense of local specificity (Vincent, 2016). Impact evaluation at scale involves challenges related to choice of indicators and effects of heterogeneity (Baylis et al., 2016; Vincent, 2016), but monitoring to track fine-scale ecological and socio-economic

impacts at many sites will be costly. The conservation agreements in Colombia show that an effective biodiversity monitoring framework capable of capturing local detail is essential to determine whether an agreement is accomplishing its conservation goals, especially if sustainable harvesting of focal species is an ultimate objective.

The Colombian Amazon experience suggests that meaningful monitoring in large-scale programmes would benefit from site-specific partnerships between communities, universities and research centres, and implementing organizations. Experience in other national and large-scale payment for ecosystem services programmes using conservation agreements confirms the value of such multi-stakeholder collaboration (de Koning et al., 2011; Espinoza et al., 2015). Although replication and scale-up are needed to increase overall impact, local-level focus remains essential to ensure demonstrable outcomes.

Acknowledgements

The following supported monitoring and documentation of project impacts in La Pedrera: Mulago Foundation, CorpoAmazonía, Mitsubishi Corporation Foundation for the Americas, Toyota Environmental Activities Grant Program, Swift Family Foundation, and the Conservation Agreements Private Partnership Platform (funded by the Global Environmental Facility through the United Nations Environment Programme). We thank the communities of Borikada, Curare, Camaritagua, Puerto Ñumi, Bocas del Taraira, Madroño and Villa Marcela, and the teams who worked with them to collect information. We also thank two anonymous reviewers for thorough and thoughtful input that greatly improved the article.

Author contributions

MM supervised the research effort and drafted sections of the article. EP compiled data and background information. EN conceptualized and wrote the article. All authors reviewed and provided substantive comment on the manuscript and approved the final version.

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