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Sustainability of small-scale fisheries in the middle Negro River (Amazonas – Brazil): A model with operational and biological variables

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ABSTRACT

Fishing is a traditional and important activity in the Amazon Basin, mainly for low-income populations. Nevertheless, Amazonian fish diversity and abundance is threatened by several anthropogenic sources, including deforestation, hydroelectric dams, oil and gas development, global changes and overfishing. This article analyzes the proposal of an alternative model and discusses the predictions obtained from various scenarios and relates them to the management of commercial fishing in the region of the middle Negro River. The model was developed using Stella® 9.0, a software package based on system dynamics. Two scenarios were simulated to investigate the dynamics of the fish stock: (a) scenario I: considered a reduction in stock replacement values to half the initial values, a 50% increase in fishing effort, and variable costs and average monthly prices of fish, and; (B) scenario II: analyzed the effect of prohibiting commercial fishing. The planning horizon used was 120 months. Given the results achieved by the simulations, it would be interesting for authorities in the region to have effective control over fishing access and for users to be aware that these natural resources, even though renewable, are susceptible to depletion.

1. Introduction

Fresh water accounts for only 0.01% of the world's water and approximately 0.8% of the Earth's surface (Gleick, 1996; Dudgeon et al., 2006), and fresh water is home to thousands of species that contribute to food security (Brooks et al., 2016). Globally, at least 2 billion people rely directly on freshwater, such as lakes, rivers and wetlands, for their food supply. In many localities, particularly in rural communities, fish is a major source of protein (Béné et al., 2007; Dugan et al., 2010; Youn et al., 2014). In 2014, fisheries catches yielded approximately 12 million tonnes (FAO, 2016), and these fisheries support at least 21 million fishers, many of whom live in low-income countries and rely on these fisheries for subsistence. They are often the last resort when primary income sources fail due to economic changes and natural disasters (Lynch et al., 2016). In addition to other important benefits, such as recreation, cultural and even spiritual values, fisheries contribute to the diversity of species and ecosystems.

Fish ecosystems are complex and difficult to analyze; however, modeling the ecosystem can minimize some of these difficulties. One of the benefits of modeling is that it enables a mathematical framework to be used to integrate field data with ecological theory, allowing the problem to be understood and simulated through the use of different scenarios. Ecosystem simulation models are used to investigate possible environmental impacts on fish populations, and different models have been developed (Polovina, 1984; Deangelis and Cushman, 1990; Christensen and Pauly, 1992; Salvanes et al., 1992; Walters et al., 1997; Grasso, 1998; Walters et al., 2000; Fu et al., 2015; Storch et al., 2017). Nevertheless, the use of ecosystem modeling is relatively new in the Amazon. Souza

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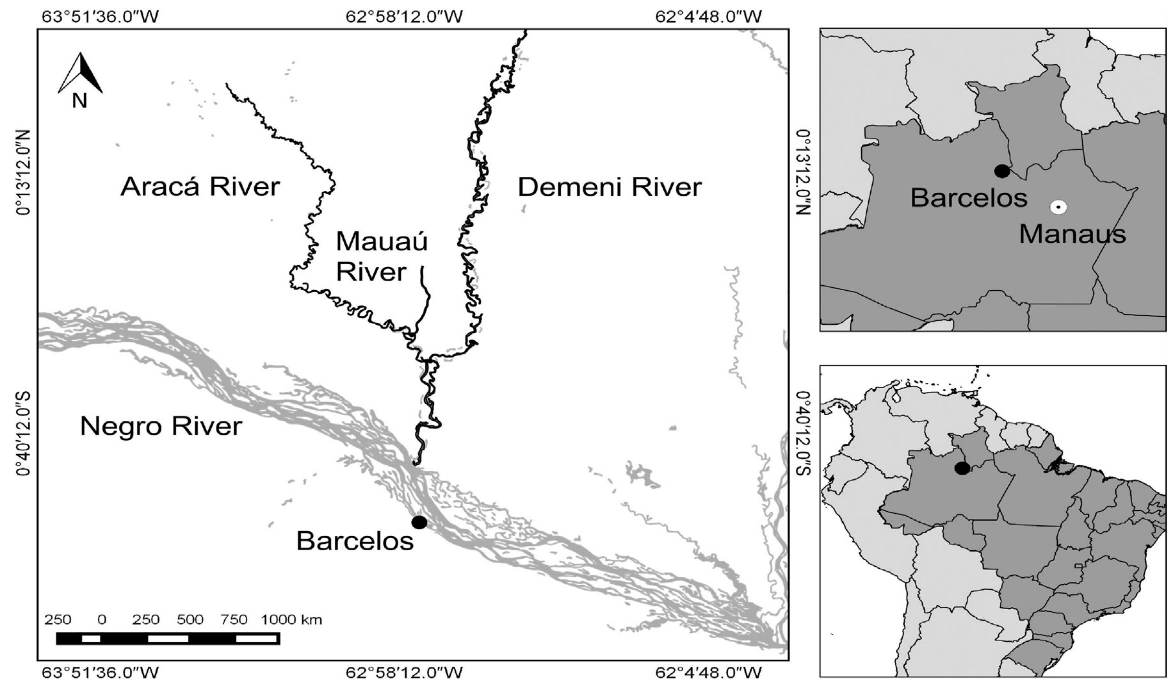

Fig. 1. Maps showing the study area; Map of South America showing Brazil; Map of the Amazonas State showing the municipality of Barcelos; Map the municipality of Barcelos showing the Negro, Aracá and Demeni rivers.

(2003) used this approach to assess the sustainability of subsistence fishing on a stretch of the Solimões River, taking into account the dynamics of the stock and fishing effort. Camargo and Petrere (2004) characterized the fishers and fisheries of the Tucuruí hydroelectric reservoir and created scenarios to predict situations of conflict over scarce resources. Souza and Freitas (2010) tested a predator-prey model, using humans as the predator and the fishing stock as the prey to evaluate fishing sustainability in the lower stretch of the Solimões River.

The Amazon Basin encompasses more than seven million km^2, which include an enormous and heterogeneous system of rivers, lakes, channels and streams. This ecosystem is home to the world's highest diversity of fish (Reis et al., 2016). Several anthropogenic factors, such as dam building (Kahn et al., 2014), oil and gas development (Finer et al., 2008), overfishing (Campos et al., 2015), invasive alien species (Latini and Petrere, 2004), deforestation (Lobón-Cerviá et al., 2015), and droughts caused by deforestation and global warming (Castello et al., 2013; Freitas et al., 2013), threaten this system.

The Negro River is the second largest tributary of the Amazonas River and is a typical blackwater river. It is known for its high diversity and low abundance of individual fish species compared with whitewater rivers (Barthem and Goulding, 2007). It contains approximately 950 described species, of which at least 35 are endemic. Much of the wealth generated in the municipality of Barcelos used to derive from the exploitation of ornamental fish, which accounted for over 60% of the municipality's income (Sobreiro and Freitas, 2008). However, this activity declined in recent years because of factors such as competition with other Amazonian regions and the retraction of the international market; thus, many fishers migrated to commercial fishing. In addition, more recently, fishers have switched to activities related to recreational fishing (Silva 2003; Sobreiro and Freitas 2008; Rivas et al., 2013). As in other regions in the Amazon basin, though fishers have other activities, such as subsistence agriculture and the extraction and commercialization of non-timber forest products (Sobreiro and Freitas, 2008; Rivas et al., 2013; Inomata and Freitas, 2015a), fishing is one of the most important economic activities for the population of the middle Negro River, who depend on fishing for their survival. Subsistence fishing is practiced by fishers in rural areas, primarily for their own consumption; distribution is secondary, and usually involves exchanges or small-scale sales.

This article analyzes the proposal of an alternative model and discusses the predictions obtained by scenarios that may influence the management of commercial fishing in the region of the middle Negro River. The model integrated the dynamics of fishers, which were influenced by economic factors, with the dynamics of the fishery resources, which considered the intrinsic characteristics of the three main groups of exploited species and the influence of the hydrological cycle.

2. Methods

2.1. Study area

The study was carried out in the middle Negro River region and focused on the municipality of Barcelos, which extends over an area of 122,450.769 km^2 (IBGE, 2015) in the northwestern region of the state of Amazonas (Fig. 1). The Negro River, which starts in the Junaí mountain range in Colombia, is the largest tributary of the Amazon River. It is approximately 1700 km long, and its basin extends over 715,000 km^2. The Negro River eventually joins the Solimões River to form the Amazon River; however, throughout its course, it drains low-lying areas and consolidated soils, which is reflected by its speed and erosion (Sioli 1984; Cunha and Pascoaloto, 2006).

2.2. Model

2.2.1. Data collection

Models are abstractions of reality, and they are unable to involve all the parameters in the modeled system since models sometimes require data with long time series; this translates into high costs, and in some situations, these data are inaccessible or nonexistent. In the present work, the developed model consisted of real data

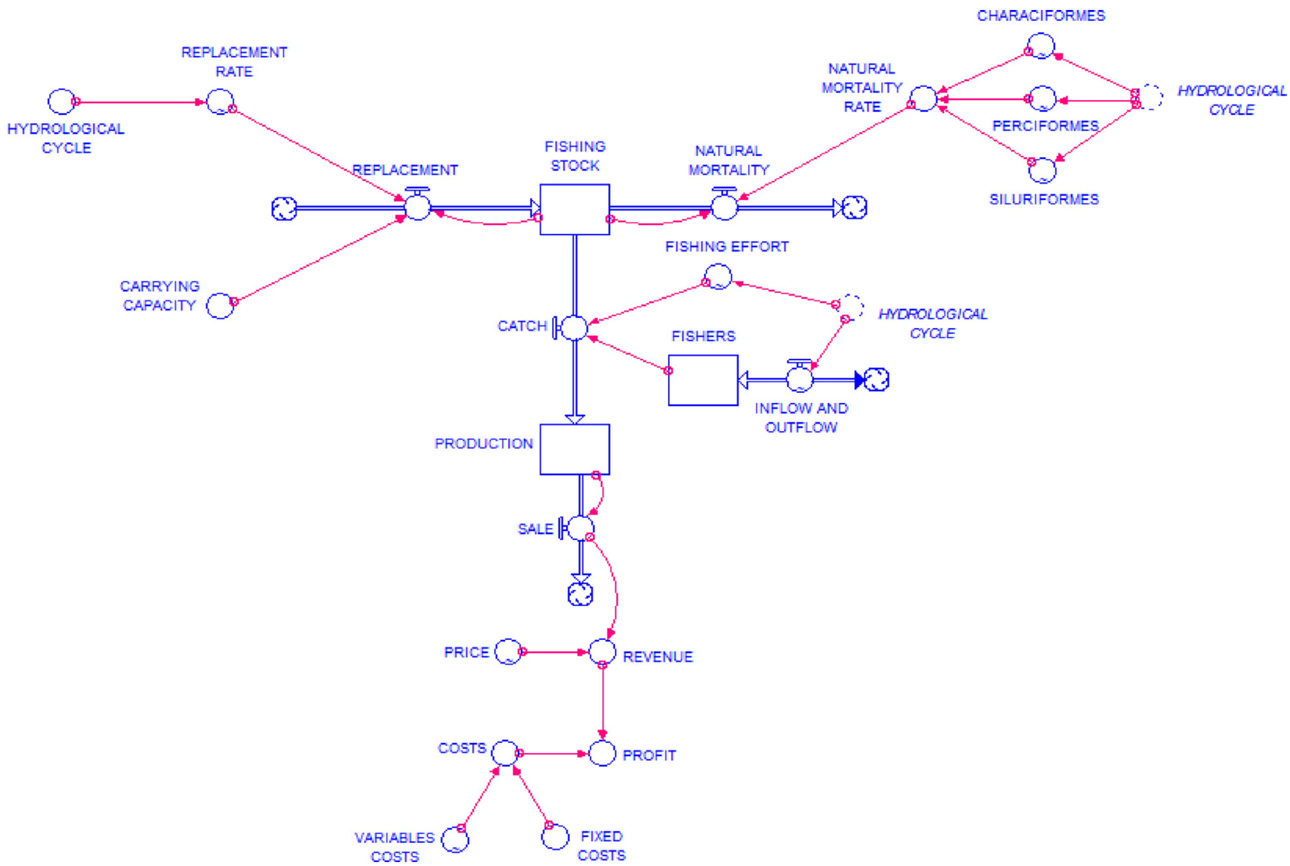

Fig. 2. Model Sustainability of Commercial Fishing in Barcelos, SCF-BO, built in software Stella. Rectangles: state variables; Circles: forcing variables; Tick arrow: material transfer and; Arrow: information variables.

that were collected using structured questionnaires applied during interviews with commercial fishers in the municipality of Barcelos between February 2012 and January 2013; additionally, the other necessary parameters were collected from the literature.

The obtained information included questions on the fishing location, number of crew members, date of departure and arrival of the expedition, hours of fishing, caught species, fishing gear, fixed and variable costs, price of fish, secondary data obtained from literature reviews (i.e., support capacity, fishing stock and natural mortality rates of Characiformes, Perciformes and Siluriformes), and information collected in January 2013 from the Barcelos Z-33 Fishers's Association (i.e., number registered commercial fishers).

2.2.2. Construction of the model

The model was called Sustainability of Commercial Fishing in Barcelos SCF-BO (Fig. 2) and combined the essential ecological and economic relationships needed to simulate the fishing system. The modeling software used was Stella v9.1.3. The model was based on system dynamics, which combined the ecological and economic variables that explained the dynamics of fishers and fishing resources by using differential equations over time (Sterman, 2002; Stave, 2002; Otto and Struben, 2004).

The integration technique used in the modeling process was Runge-Kutta 4, which is one of the recommended methods for models in which the generation of oscillations is predicted. Due to the flood pulse, the unit of time chosen was the month. The total time horizon was 120 months, and the DT was set to 0.25 since this better represents variations as a function of time for the flood pulse (see Appendix A in Supplementary material for the explanation of model equations).

2.2.3. Variables

2.2.3.1. State variables. Fishing stock: the exploitation rate in relation to the estimated biomass and the carrying capacity (Silva-Júnior et al., 2017).

Production: the captured value (kg) between February 2012 and January 2013 (Inomata and Freitas, 2015b).

Fishers: the number of commercial fishers registered in the Barcelos Z-33 Fishers's Association in January 2013.

2.2.3.2. Forcing variables. Carrying capacity: value obtained by Silva-Júnior et al. (2017) that estimated the stock size of some commercial Amazonian species based on catch and effort data. The authors used a probabilistic approach based on the work developed by Mao (2007), which estimated the lower limits of the size of a given stock. The calculations were implemented through a script called EPSCE (estimating population size with catch and effort data), which was developed and implemented in the R package. The script was submitted for validation using a set of data generated by a simulation process where the size of the population was a known value. Afterwards, the model was applied to the catch data related to weight and effort for the main commercial fish species of the Amazon; according to the data generated during the ProVárzea/IBAMA project between 2001 and 2004, information was collected from sixteen ports of landing along the Solimões and Amazonas rivers (Ruffino et al., 2002, 2005, 2006; Thomé-Souza et al., 2007).

Hydrological cycle: used the trigonometric function of the sine wave, with a period of flood and a period of dry, which always oscillated with the same amplitude (i.e., 9.54 m during the flood and 2.52 m during the dry season) over a period of 12 months. Monthly data on the water level in the Negro River (measured at the Barcelos

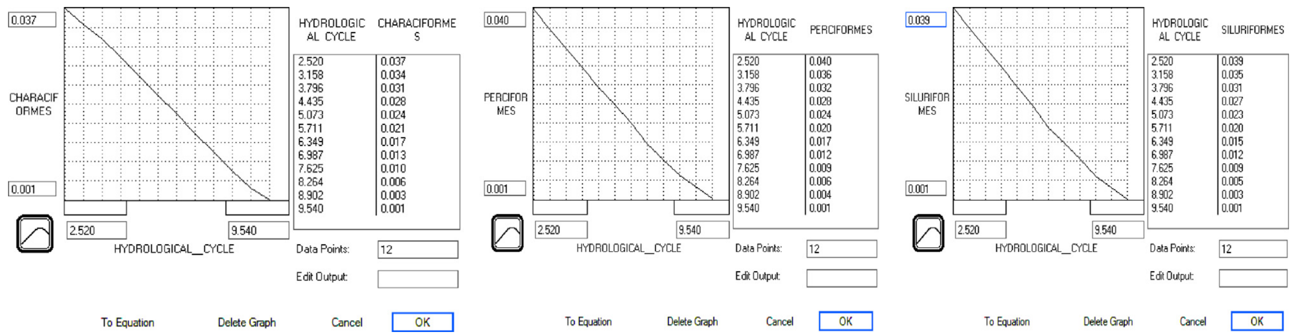

Fig. 3. Graph functions that define the relationship between the natural mortality rates of Characiformes, Perciformes and Siluriformes and the hydrological cycle.

hydrological station) were provided by the National Water Agency (ANA).

$$-\text{Sin}\, wave\left(\frac{amplitude\ above\ the\ mean}{2}, 12\right) + \frac{(\max\ mean)}{2} + \min\ mean$$

Replacement rate: established according to the hydrological cycle in an attempt to simulate the reproductive cycle of most target species in the region, following the approach developed by Souza and Freitas (2010). The maximum replacement (100%) coincided with the flood peak.

The mortality can be divided into two main groups, i.e., natural deaths and deaths that result from fishing. Natural mortality may be divided into three main categories: natural causes, such as old age or disease; fish killed by predators; and finally, fish that starve due to a lack of available food. This final category is considered to be one of the most difficult parameters to estimate for fish stocks (Quinn and Deriso, 1999). Therefore, we used the natural mortality estimates that were reported from three sources in the literature: 1) the natural mortality rates of Characiformes were estimated from the study of Isaac and Ruffino (1996); 2) the natural mortality rates of Perciformes were established according to Campos' data (2013); and 3) the natural mortality rates of Siluriformes were determined based on the work of Ruffino and Isaac (1999). The three orders were chosen to comprise the model because they were the most exploited orders in the study area (Inomata and Freitas, 2015b). All utilized literature estimated natural mortality using Pauly's (1980) empirical relationship.

A graphical function was performed for each order, and all orders were influenced by the hydrological cycle; thus, it was assumed that the highest rates of natural mortality occur during the dry period (Fig. 3). This has been associated with the physical retraction of the environment, which confines the fish in the open areas of lakes and facilitates predation.

Fishing effort: average monthly value based on the estimation of Inomata and Freitas (2015b), which used the calculation proposed by Petrere (1978), and indicated the best unit for fishing in the Amazon region was the number of fishers in a crew multiplied by the number of fishing days.

Price: average monthly value of fish, as reported by the fishers during the interviews.

Revenue: fishing revenue (R) was estimated as the number of fish caught (Q) multiplied by the average sale price of the fish (P), or R = Q*P.

Profit: defined as the total revenue minus the total costs and was estimated by deducting fixed and variable costs from income during a given period, i.e., P = R – (Cf + Cv). The fixed costs consisted of the maintenance costs associated with the vessel, engine and fishing gear; the depreciation of the vessel and engine; and the fishers' association fees. The variable costs consisted of the costs of fuel, ice and provisions for the fishing trips (Inomata and Freitas, 2015a).

2.2.3.3. Material transfer. Replacement: was represented by the logistic equation of Verhulst (1838).

$$N(t) = rN(t)\left(1 - \frac{N(t)}{K}\right)$$

where N = size of fish population; r = innate capacity for population increase; K = carrying capacity; and t = model running time.

Catch: total number of fish that are caught. Catch was estimated using the product of the total number of fishers and the fishing effort; this was considered the attack rate on the fish stock.

Sale: it was assumed that everything that was produced was sold.

Inflow and outflow of fishers: it was assumed that both the entry and exit of fishers from fishing activities was directly related to the hydrological cycle, the main regulating force of the entire ecosystem (Junk et al., 1989), which directly influences the success of the catches and results in seasonal peaks (Freitas and Rivas, 2006). In Barcelos, during the dry season, commercial fishers are dedicated exclusively to fishing activities. During the flood season, some fishers reduce their journeys or engage in other complementary activities, such as ornamental fishing and activities related to agriculture (Inomata and Freitas, 2015b).

2.2.4. Construction of scenarios

To simulate different scenarios, a set of differential equations was maintained, and changes were restricted to the input values of specific rates or derived relationships. Two scenarios were simulated using the SCF-BO model, and these scenarios considered the following changes in system characteristics:

(A) Scenario I: simulated a reduction in stock replacement values to half of the initial values. This represents an atypical situation and assumes that climate change destabilizes the aquatic environment and directly affects the replacement of the fishing stock. Fishers have a tendency to increase fishing effort when there is a decrease in fish; this practice increases production costs and, consequently, the price of fish. Therefore, in addition to the decrease in stock replacement, a 50% increase in the fishing effort, variable costs and average monthly price of fish were also simulated in this scenario.

(B) Scenario II: simulated and analyzed the effect of a total ban on commercial fishing. This scenario assumed all fishers fished only for subsistence.

3. Results

In January 2013, there were 281 commercial fishers registered in the Barcelos Z-33 Fishers's Association; however, only 160 fishers caught edible fish, and 121 were ornamental fishers. Primary

Table 1
Descriptive parameters of the SCF-BO model and the different values and units used; Input data; Form; Unit; Value (minimum and maximum); Reference.

Input data	Form	Unit	Value	Min	Max	Reference
Fishing stock	state variable	Kg	41295284	–	–	Silva-Júnior et al. (2017)
Production	state variable	Kg	56000	–	–	Inomata and Freitas (2015b)
Fishers	state variable	no individuals	160	–	–	Inomata and Freitas (2015a)
Carrying capacity	forcing variable	Kg	599843280	–	–	Silva-Júnior et al. (2017)
Hydrological cycle	forcing variable	M	–	2.52	9.54	ANA (2013)[a]
Replacement rate	forcing variable	%	–	0.000	1.000	Souza and Freitas (2010)
Natural mortality rate Characiformes	forcing variable	–	–	0.001	0.037	Isaac and Ruffino (1996)
Natural mortality rate Perciformes	forcing variable	–	–	0.001	0.040	Campos (2013)
Natural mortality rate Siluriformes	forcing variable	–	–	0.001	0.039	Ruffino and Isaac (1999)
Fishing effort	forcing variable	–	–	30.0	68.6	Inomata and Freitas (2015b)
Price	forcing variable	real (R$)	–	2.75	4.50	Inomata and Freitas (2015b)
Fixed costs[b]	forcing variable	real (R$)	431.22	–	–	Inomata and Freitas (2015a)
Variables costs	forcing variable	real (R$)	–	561.50	4272.00	Inomata and Freitas (2015a)

[a] Information provided to the authors by the National Water Agency (ANA) in February 2013.
[b] Average costs in Reais (R$). Prices charged in January 2013.

Table 2
List of minimum and maximum values of the fish stock (kg), production (kg) and profit (R$) of the model, including current trends of the system (BaU), scenario I and scenario II.

	Fishing Stock (kg)		Production (kg)		Profit (R$)	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
BaU	4.13e + 007	5.961e + 008	21783.53	881392.73	88235.48	3.353e + 006
Scenario I	4.13e + 007	5.805e + 008	34542.40	1.763e + 006	234258.48	1.342e + 007
Scenario II	4.13e + 007	5.964e + 008	–	–	–	–

data were collected from 161 fishing expeditions, and 125 fishers were interviewed, representing 44.5% of the registered population of commercial fishers. The data used in the model feed are listed in Table 1.

The dynamics of the model with the current trends of the system (BaU) demonstrated the fish stock had a minimum value of 4.13e + 007 and a maximum value of 5.961e + 008. Production had a minimum value of 21783.53 and a maximum value of 881392.73, and the activity had a minimum profit of R$ 88235.48 and a maximum profit of R$ 3.353 + 006 (Table 2).

When comparing scenario I with BaU, this simulation showed that the fishing stock decreased (Fig. 4A). However, the production and profit increased (Fig. 4B and C), with minimum and maximum production values of 34542.40 kg and 1.763e + 006 kg, respectively, and minimum and maximum profit values of R$ 234258.48 and R$ 1.342e + 007, respectively (Table 2).

In scenario II, the effect of prohibiting commercial fishing was analyzed; therefore, economic variables were excluded. In this simulation, the dynamics of the fishing stock were similar to BaU (Fig. 4A); however, there was a small increase in the maximum value (Table 2).

3.1. Sensitivity analysis

To explore how the model responded to changes in input variables, a sensitivity analysis was performed. The values of the variables were changed several times, using higher uncertainties each time. After the analysis, it was possible to verify the robustness of the model since it presented the same general behavior.

The variables on support capacity, fish stock and number of fishers were modified. The results showed that (A) the fish stock decreased considerably with 35% and 70% reductions in the initial carrying capacity value; (B) the fish stock slightly decreased after the 35% and 70% changes in the simulated value in BaU; and (C) production and profit followed the same pattern after increasing the initial value of the number of fishers by 200 and 400% (Fig. 5).

4. Discussion

The insertion of the hydrological cycle as a forcing variable was essential to make the simulations more realistic; this is because the biological cycles of Amazonian fish are strongly dependent on hydrological events (Junk et al., 1989), mainly during the flood season when most species reproduce (Fernandes, 1997). The highest level of productivity occurs during the dry season. At the moment, fish are more concentrated and vulnerable to fishing gear. The link between river level oscillations and fishery productivity is a widely recognized process in the Amazon Basin (Junk et al., 1989; Ruffino and Isaac 1994; Isaac et al., 2016).

In recent years, Amazonia has suffered from atypical oscillations at the river level, with the occurrence of extreme droughts and floods (França et al., 2005; Ambrizzi et al., 2007; Marengo, 2007). These changes have been attributed to the effects of climate change (Marengo et al., 2011) and may interfere with the life cycle of the fish, the fishery, and consequently, the fishers and riverine fish that survive fishing activities (Allison et al., 2009).

The simulations showed that the commercial fishing carried out in the municipality of Barcelos may possibly be sustainable. If, however, the fish population declined as simulated in scenario I, fishers would experience lower profits. To maintain the same profit, they would have to increase their fishing effort without control and limits; thus, the operational costs per unit of fish would progressively increase, and this would affect even more of the biological cycle of natural replenishment for the most exploited species, resulting in overfishing and compromising economic performance.

Even if some fishers realized the danger of overfishing, there is no guarantee that their competitors would perceive the same danger. Individual short-term profits motivate many fishers. They do not care about the resource involved. If each fisherman acts individually to maximize profit, the total effective cost can easily surpass the sustainable limit and, thus, create the risk of overfishing, which harms the interest of all fishers in a process known as the “tragedy of the commons” (Hardin, 1968).

Furthermore, fishers face the growing threat of scarcer resources that are more vulnerable to damage, making them likely to seek

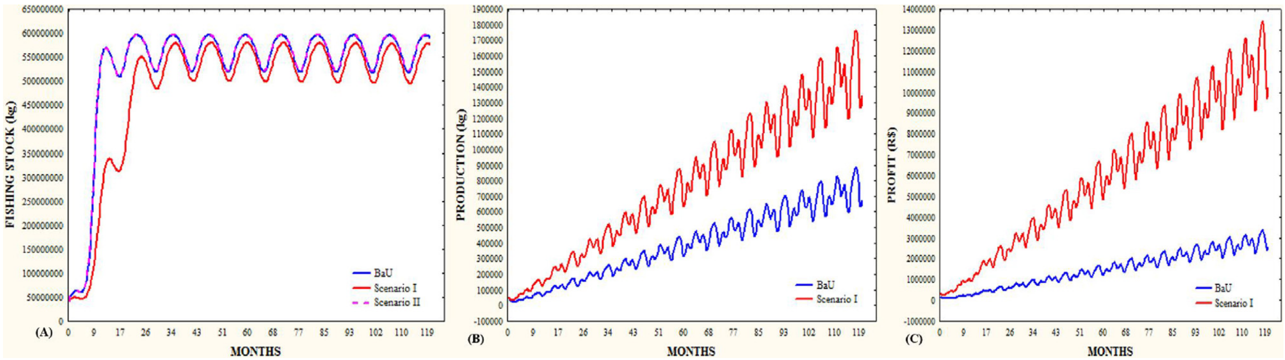

Fig. 4. Results of the dynamics of the fishing stock (A), production (B) and profit (C) obtained in each of the simulated scenarios. Business as Usual (BaU). Scenario I: considered a reduction in stock replacement values to half the initial values. In addition, scenario I also simulated a 50% increase in the fishing effort, variable costs and average monthly price of fish. Scenario II: analyzed the effect of a total ban on commercial fishing.

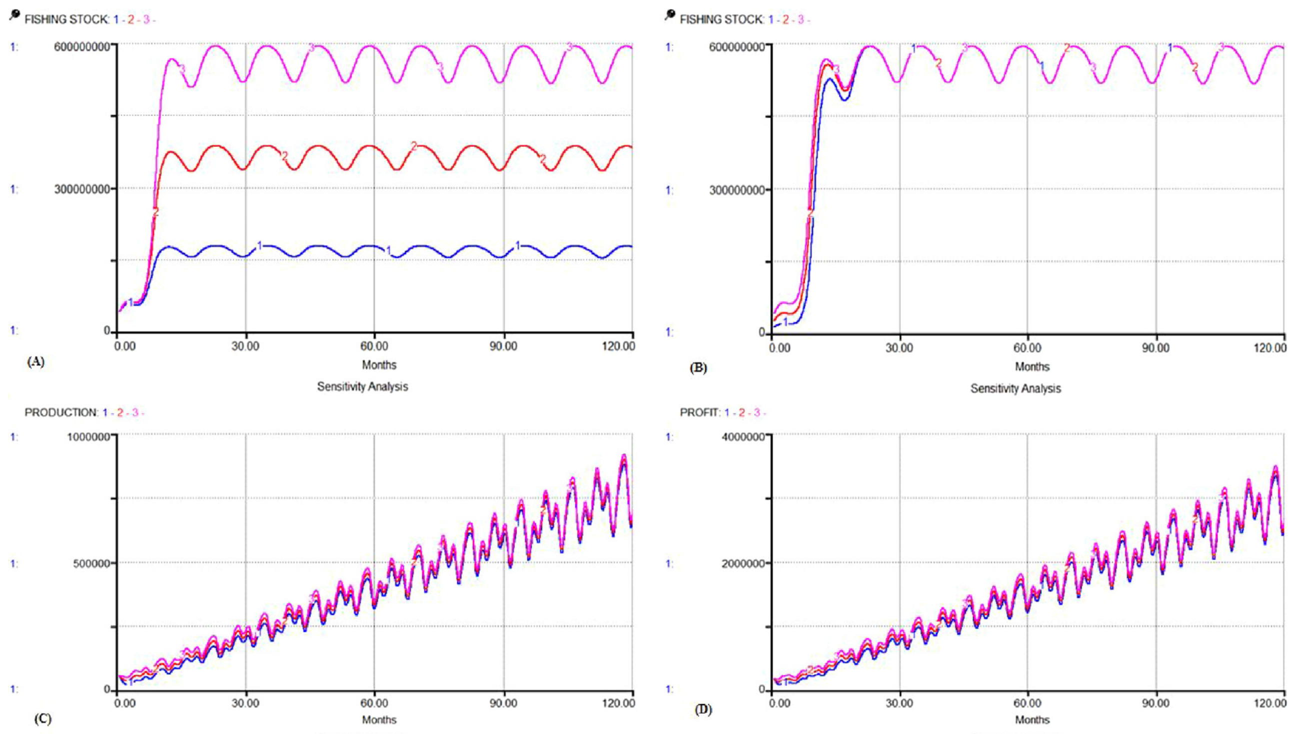

Fig. 5. Graphs resulting from sensitivity analysis for the available variables. (A) Fishing stock after decreasing carrying capacity (1: 70% smaller; 2: 35% smaller; and 3: BaU data); (B) Decrease in the fishing stock (1: 70% smaller; 2: 35% smaller; and 3: BaU data); (C) Production after increasing the number of fishers (1: BaU data; 2: 200% higher; and 3: 400% higher; and (D) Profit after increasing the number of fishers (1: BaU data; 2: 200% higher; and 3: 400% higher).

out technological innovations that will maximize their catch; certainly, the search for technological innovations is common when some means of production becomes scarce. The region of the middle Negro River as well as the entire Amazon is undergoing a process of intensification in the use of fish resources; this intensification is caused by technological innovations, loss of control over areas and resources, population growth, migration and urbanization (Silva, 2011). According to Berkes (1999), these events can lead to the loss of traditional knowledge, the breakdown of traditional social and economic systems, the loss of control over areas and resources by local communities, and changes in the worldview caused by urbanization.

Scenario II was the most appropriate for the sustainable use of fishery resources since commercial fishing was prohibited. However, in this case, there would be a great impact on the way of life of fishers, since the high proportion of fishers (56.9%) with commercial fishing as their exclusive economic activity suggests that this activity is traditional in the region. This impact could result in commercial fishers targeting catches in more distant areas, migrating to areas with a more plentiful supply of fish or even taking up other activities.

The possibility of migrating to more distant areas was only a supposition of what may occur, as commercial fishers from Barcelos have already reported the need to fish larger areas to capture the same quantity of fish they used to catch in the past. Moreover, this is already occurring in other regions studied in the Amazon (Petrere, 1978; Barthem et al., 1997). However, the geographical component was not part of the model.

As for fishers migrating to other activities, such as ornamental fishing and sport fishing, this migration would lead to the intensification of conflicts between the different users; conflict would likely start once the resources became scarce, which would generate greater pressure on the selection of users. Most likely, more specialized fishers would exclude others from the activity, which could cause declines in the target species or even deplete the resource as a whole.

Freitas and Rivas (2006) and Sobreiro and Freitas (2008) reported that the overlapping of fishing areas in the middle Negro River region and the different ways in which users take ownership of these areas has led to the emergence of conflicts between different users. The growth of sport fishing has created conflict among subsistence fishers, ornamental fishers and, above all, commercial fishers. The conflict between subsistence fishers and ornamental fishers is minimized by the fact that the latter can act as guides or boat pilots for sport fishers. The conflict between subsistence fishers and commercial fishers results from the different understandings of the target species, i.e., the peacock bass (*Cichla* spp.). These species are one of the main groups of species exploited by commercial fishing (Inomata and Freitas, 2015b), and *Cichla* spp. are one of the main groups of target species for sport fishing in the middle Negro River (Freitas and Rivas, 2006). According to Silva (2011), the increased pressure on fishery resources in this region, whether through sport or commercial fishing, is perceived as a threat to natural fish stocks.

Fishing is an extremely competitive activity. While there are fish stocks, there will be competition between different users due to the lack of property rights governing the use of fish resources (Castello, 2007). Each fisherman will capture as many fish as possible, especially the most profitable species. Murray-Jones and Steffe (2000) and Warner (2000) reported that such conflicts can be resolved or at least reduced through agreements between the involved parties and the creation of a management plan.

The simulations in the present study resulted in predictions that did not lead to the collapse of the fishery. However, this information is important, since a limit to the sustainability of the stock can be established from the unsustainable probabilities of exploiting a resource (Aubone, 2004). As fish are an essential source of animal protein and an important source of income in the region, it is important that the fisheries be monitored more closely by users and fishing activity managers. This monitoring is especially important in the Negro River basin because, despite the great diversity of fish species, the basin has low biomass stocks of individual species compared to whitewater rivers (Barthem and Goulding, 2007).

It would be interesting if, as a management measure for the region, there was an effective control method to limit the access to fisheries. According to Castello (2007), to maintain fish production at a sustainable limit, control measures that reduce pressure on fish stocks and help manage resources are essential. These measures would be more related to the administration of human dynamics than to the control of the resource itself. Given the growing threat natural resource scarcity caused by the use of conventional economic systems where natural resources are considered unlimited, it is important that all those engaged in fishing activities in the region participate directly in the formulation of management measures and objectives, help develop rules, make changes and adaptations that may be necessary, and, above all, contribute to the application of management (Bell and Morse, 2008).

Public policies should also include environmental education strategies. These strategies would inform users that the fishery resources, even though they are renewable, are also subject to depletion; additionally, the public should know that the characteristics of the environment can influence the fishery. When an individual is not critically aware of the negative impacts an activity has in relation to the intensive use of resources, he does not have the capacity to evaluate the losses from a social, economic or environmental point of view (Castello, 2007), nor does he have the dimension to realize how certain actions may actually counteract his own assets and those of future generations. In this way, control actions that promote the participation of those involved in fishing practices and promote the access to knowledge on environmental conservation that is based on respect for regional specificities are necessary.

5. Conclusion

The ecosystem model described here integrates ecological and economic variables and appears to be a promising tool for testing hypotheses and formulating and monitoring management scenarios related to possible changes in the exploitation of fishery resources. However, it must be emphasized that the elaborated model is only a proposal of an alternative model for the evaluation and management of the fishery and is not meant to replace the classic models or traditional practices in which users are trained to implement a participatory system.

The results reported should be evaluated carefully since the information was collected over only one year; however, this information can be used as a point of reference in time. Therefore, it is recommended that data be collected continuously in this region to produce a time series, enabling validation of the model so that it can be used as an analysis and management tool. Furthermore, for the model to meet regional needs, field studies that collect information on the population dynamics of Amazonian fishes are essential.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ecolmodel.2017.11.025.

References

Allison, E.H., Perry, A.L., Badjeck, M., Adger, W.N., Brown, K., Conway, D., Halls, A.S., Pilling, G.M., Reynolds, J.D., Andrew, N.L., Dulvy, N.K., 2009. Vulnerability of national economies to the impacts of climate change on fisheries. Fish Fish. 10 (1), 173–196.

Ambrizzi, T., Rocha, R.P., Marengo, J.A., Pisnitchenko, I., Alves, L.M., Fernandez, J.P.R., 2007. Cenários regionalizados de clima no Brasil e América do Sul para o Século XXI: Projeções de clima futuro usando três modelos regionais. Relatório 3. Ministério do Meio Ambiente (MMA), Secretaria de Biodiversidade e Florestas (SBF), Diretoria de Conservação da Biodiversidade (DCBio), São Paulo.

Aubone, A., 2004. Threshold for sustainable exploitation of an age-structured fishery stock. Ecol. Modell. 173, 95–107.

Béné, C., Macfadyen, G., Allison, E.H., 2007. Increasing the contribution of small-scale fisheries to poverty alleviation and food security. In: Fisheries Technical Paper. No. 481. Food and Agriculture Organization of the United Nations, Rome, Italy, 97 pp.

Barthem, R.B., Goulding, M., 2007. Um ecossistema inesperado: a Amazônia revelada pela pesca. Amazon Conservation Association (ACA), Sociedade Civil Mamirauá, Belém, 241 pp.

Barthem, R.B., Petrere, M., Isaac, V.N., Ribeiro, M.C.L.B., McGrath, D.G., Vieira, I.J.A., Barco, N.V., 1997. A pesca na Amazônia: problemas e perspectivas para o seu manejo. In: Valadares-Pádua, C., Bodmer, R.E., Cullen, L. (Eds.), Manejo de vida silvestre para a conservação no Brasil. CNPq/Sociedade Civil Mamirauá, Belém, Pará, pp. 173–185.

Bell, S., Morse, S., 2008. Sustainability Indicators: Measuring the Immeasurable, 2ª ed. Earthscan Publications Ltd., London, ISBN-13: 978-1-84407-299-6 (pbk.) 251 pp.

Berkes, F., 1999. Sacred Ecology: Traditional Ecological Knowledge and Resource Management. Taylor & Francis, Ann Arbor.

Brooks, E.G.E., Holland, R.A., Darwall, W.R.T., Eigenbrod, F., 2016. Global evidence of positive impacts of freshwater biodiversity on fishery yields. Glob. Ecol. Biogeogr. 25 (5), 553–562.

Camargo, S.A.F., Petrere, M., 2004. Análise de risco aplicada ao manejo precaucionário das pescarias artesanais na região do Reservatório da UHE-Tucuruí (Pará-Brasil). Acta Amazonica 34 (3), 473–485.

Campos, C.P., 2013. Dinâmica populacional do tucunaré *Cichla temensis* (Humboldt, 1833) do Médio rio Negro, Amazonas, Brasil. Dissertação de Mestrado – INPA, Programa de Pós-Graduação em Biologia de Água Doce e Pesca Interior, Manaus, 55 pp.

Campos, C.P., Garcez, R.C.S., Catarino, M., Costa, G.A., Freitas, C.E.C., 2015. Population dynamics and stock assessment of *Colossoma macropomum* caught in Manacapuru lake system (Amazon Basin, Brazil). Fish. Manage. Ecol. 22, 400–406.

Castello, L., McGrath, D.G., Hess, L.L., Coe, M.T., Lefevre, P.A., Petry, P., Macedo, M.N., Renó, V.F., Arantes, C.C., 2013. The vulnerability of Amazon freshwater ecosystems. Conserv. Lett. 6, 217–229.

Castello, J.P., 2007. Gestão sustentável dos recursos pesqueiros, isto é realmente possível? Pan-Am. J. Aquatic Sci. 2 (1), 47–52.

Christensen, V., Pauly, D., 1992. ECOPATH II: a software for balancing steady-state models and calculating network characteristics. Ecol. Modell. 61, 169–185.

Cunha, H.B., Pascoaloto, D., 2006. Hidroquímica dos rios da Amazônia. Manaus: Governo do Estado do Amazonas. Secretaria de Estado da Cultura; Centro Cultural dos Povos da Amazônia, 127 pp. (Série Pesquisas).

Deangelis, D.L., Cushman, R.M., 1990. Potential application of models in forecasting the effects of climate changes on fisheries. Trans. Am. Fish. Soc. 119 (2), 224–239.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.-I., Knowler, D.J., Leveque, C., Naiman, R.J., Prieur-Richard, A.-H., Soto, D., Stiassny, M.L.J., Sullivan, C.A., 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. Biol. Rev. 81, 163–182.

Dugan, P., Delaporte, A., Andrew, N., O'Keefe, M., Welcomme, R.L., 2010. Blue Harvest: Inland Fisheries as an Ecosystem Service. UNEP, World Fish Center, Penang, Malaysia, 68 pp.

FAO, 2016. The State of World Fisheries and Aquaculture 2016, Retrieved 20 August 2017, from http://www.fao.org/3/a-i5555e.pdf.

Fernandes, C.C., 1997. Lateral migrations of fishes in Amazon floodplains. Ecol. Freshw. Fish 2, 36–44.

Finer, M., Jenkins, C.N., Pimm, S.L., Keane, B., Ross, C., 2008. Oil and gas projects in the Western Amazon: threats to wilderness, biodiversity, and indigenous people. PLoS One 3, 1–9, http://dx.doi.org/10.1371/fournal.pone.0002932.

França, A.M.S., Gallotti, T.F., Novo, E.M.L.M., 2005. A dinâmica do pulso de inundação: aplicações de sensoriamento remoto na estimativa da área de expansão dos sistemas lacustres da planície aluvial do rio Amazonas. In: XI Simpósio Brasileiro de Geografia Física Aplicada, São Paulo: Anais do SBGFA, pp. 2742–2750.

Freitas, C.E.C., Rivas, A.A.F., 2006. A pesca e os recursos pesqueiros na Amazônia Ocidental. Ciência e Cultura [online] 58 (3), 30–32, ISSN 0009-6725.

Freitas, C.E.C., Siqueira-Souza, F.K., Humston, R., Hurd, L.E., 2013. An initial assessment of drought sensitivity in Amazonian fish communities. Hydrobiologia 705, 159–171.

Fu, C., Large, S., Knight, B., Richardson, A., Bundy, A., Reygondeau, G., Boldt, J., Van der Meeren, G.I., Torres, M.A., Sobrino, I., Auber, A., Travers-Trolet, M., Piroddi, C., Diallo, I., Jouffre, D., Mendes, H., Borges, M.F., Lynam, C., Coll, M., Shannon, L.J., Shin, Y.J., 2015. Relationships among fisheries exploitation, environmental conditions, and ecological indicators across a series of marine ecosystems. J. Mar. Syst. 148, 101–111.

Gleick, P.H., 1996. Water resources. In: Schneider, S.H. (Ed.), Encyclopedia of Climate and Weather. Oxford University Press, New York, USA, pp. 817–823.

Grasso, M., 1998. Ecological-economic model for optimal mangrove trade-off between forestry and fishery production: comparing a dynamic optimization and a simulation model. Ecol. Modell. 112 (2–3), 131–150.

Hardin, G., 1968. The tragedy of commons. Science, 1243–1248.

Instituto Brasileiro de Geografia e Estatística. Retrieved: 27 March 2017, from http://www.ibge.gov.br/home/.

Inomata, S.O., Freitas, C.E.C., 2015a. A pesca comercial no Médio rio Negro: aspectos econômicos e estrutura operacional. Boletim do Instituto de Pesca 41 (1), 79–87.

Inomata, S.O., Freitas, C.E.C., 2015b. Fish landings in Barcelos, in the Middle Negro River Region, Amazonas. In: Miralles-Garcia, J.L., Brebbia, C.A. (Eds.), Ecosystems and Sustainable Development, 90, 1 ed. WIT Press, USA, pp. 67–76.

Isaac, V.J., Ruffino, M.L., 1996. Population dynamics of tambaqui, *Colossoma macropomum* Cuvier, in the Lower Amazon, Brazil. Fish. Manage. Ecol. 3, 315–333.

Isaac, V.J., Castello, L., Santos, P.R.B., Ruffino, M.L., 2016. Seasonal and interannual dynamics of river-floodplains multispecies fisheries in relation to flood pulses in Lower Amazon. Fish. Res. 183, 352–359.

Junk, W.J., Bayley, P.B., Sparks, R.E., 1989. The flood pulse concept in river-floodplain systems. Spec. Publ. Can. J. Fish. Aquatic Sci. 106, 110–127.

Kahn, J.R., Freitas, C.E.C., Petrere, M., 2014. False shades of green: the case of Brazilian Amazonian hydropower. Energies 7, 6063–6082.

Latini, A.O., Petrere, M., 2004. Reduction of a native fish fauna by alien species: an example from Brazilian freshwater tropical lakes. Fish. Manage. Ecol. 11, 71–79.

Lobón-Cerviá, J., Hess, L.L., Melack, J.M., Araújo-Lima, C.A.R.M., 2015. The importance of forest cover for fish richness and abundance on the Amazon floodplain. Hydrobiologia 750, 245–255.

Lynch, A.J., Cooke, S.J., Deines, A., Bower, S., Bunnell, D.B., Cowx, I.G., Nguyen, V.M., Nonher, J., Phouthavong, K., Riley, B., Rogers, M.W., Taylor, W.W., Woelmer, W., Youn, S.-J., Beard Jr., T.D., 2016. The social, economic, and ecological importance of inland fishes and fisheries. Environ. Rev. 24, 115–121.

Mao, C.X., 2007. Estimating population sizes by catch-effort methods. Stat. Methodol. 4 (1), 111–119.

Marengo, J.A., Chou, S.C., Betts, R., Kay, G., Alves, L.M., Torres, R., Santos, D., Lyra, A.A., Sueiro, G., Betts, R., Chagas, D.J., Gomes, J.L., Bustamente, J.F., Tavares, P., 2011. Development of regional climate change scenarios in South America using the Eta CPTEC/HadCM3 climate change projections: Part 1. Climatology and regional analyses for the Amazon, São Francisco and the Parana River Basins. Climate Dynamics, 1. Springer-Verlag, pp. 1–20, 1.

Marengo, J.A., 2007. Mudanças climáticas globais e seus efeitos sobre a biodiversidade caracterização do clima atual e definição das alterações climáticas para o território brasileiro ao longo do século XXI. Ministério do Meio Ambiente, Brasília.

Murray-Jones, S., Steffe, A.S., 2000. A comparison between the commercial and recreational fisheries of the surf clam, Donax deltoides. Fish. Res. 44, 219–233.

National Water Agency-ANA, 2013. Portal SNIRH System Hidroweb. Retrieved 05 February 2013, from http://www.snirh.gov.br/hidroweb/.

Otto, P., Struben, J., 2004. Gloucester fishery: insights from a group modeling intervention. Syst. Dyn. Rev. 20, 287–312.

Pauly, D., 1980. On the interrelationships between natural mortality, growth parameters, and environmental temperature in 175 fish stocks. ICES 39 (2), 175–192.

Petrere, M., 1978. Pesca e esforço de pesca no estado do Amazonas. II—Locais e aparelhos de captura e estatística dmme desembarque. Acta Amazonica 8 (2), 1–54.

Polovina, J.J., 1984. Model of a coral reef ecosystem I: the ECOPATH model and its application to French Frigate Shoals. Coral Reefs 3, 1–11.

Quinn, T.J., Deriso, R.B., 1999. Quantitative Fish Dynamic. Oxford University Press, New York, 542 pp.

Reis, R.E., Albert, J.S., Di Dario, F., Mincarone, M.M., Petry, P., Rocha, L.A., 2016. Fish biodiversity and conservation in South America. J. Fish Biol. 89 (1), 12–47.

Rivas, A.A.F., Kahn, J.R., Freitas, C.E.C., Hurd, L.E., Cooper, G., 2013. The role of payments for ecological services in the sustainable development and environment preservation of the rainforest: a case study of Barcelos, Amazonas, BR. Int. J. Soc. Ecol. Sustain. Dev. 4, 13–27.

Ruffino, M.L., Isaac, V.J., 1994. Las pesquerias del bajo Amazonas: problemas de manejo y desarrolo. Acta Biologica Venezuela 15 (2), 37–46.

Ruffino, M.L., Isaac, V.J., 1999. Dinâmica populacional do surubim-tigre *Pseudoplatystoma tigrinum* (Valenciennes, 1840) no Médio Amazonas (Siluriforme, Pimelodidae). Acta Amazonica 29 (3), 463–476.

Ruffino, M.L., Oliveira, C., Viana, J.P., Barthem, R.B., Batista, V.S., Isaac, V.J., 2002. Estatística Pesqueira do Amazonas e Pará-2001. ProVárzea/IBAMA, 84 pp.

Ruffino, M.L., Silva Jr, U., Soares, E.C., Silva, C.O., Barthem, R.B., Batista, V.S., Estupiñan, G., Isaac, V.J., Fonseca, S., Pinto, W., 2005. Estatística Pesqueira do Amazonas e Pará-2002. ProVárzea/IBAMA, 84 pp.

Ruffino, M.L., Soares, E.C., Silva, C.O., Barthem, R.B., Batista, V.S., Estupiñan, G., Pinro, W., 2006. Estatística Pesqueira do Amazonas e Pará-2003. ProVárzea/IBAMA, 76 pp.

Salvanes, A.G.V., Aksnes, D.L., Giske, J., 1992. Ecosystem model for evaluating potential cod production in a west Norwegian fjord. Mar. Ecol. Prog. Ser. 90, 9–22.

Silva, A.L., 2003. Uso de recursos por populações ribeirinhas do Médio rio Negro. Tese (Doutorado) Universidade de São Paulo, São Paulo-SP, 237 pp.

Silva, A.L., 2011. Entre tradições e modernidade: conhecimento ecológico local, conflitos de pesca e manejo pesqueiro no rio Negro, Brasil. Boletim Museu Paraense Emílio Goeldi. Ciência Humana. Belém 6 (1), 141–163.

Silva-Júnior, U.L., Raseira, M.B., Ruffino, M.L., Batista, V.S., Leite, R.G., 2017. Estimativas do tamanho do estoque de algumas espécies de peixes comerciais da Amazônia a partir de dados de captura e esforço. Biodiversidade Brasileira 7 (1), 105–121.

Sioli, H., 1984. The Amazon and its main effluents: hydrography, morphology of the river courses, and river types. In: Sioli, H. (Ed.), The Amazon, Limnology and Landscape Ecology of a Mighty Tropical River and Its Basin. Dr. W. Junk Publishers, Dordrecht, pp. 127–166.

Sobreiro, T., Freitas, C.E.C., 2008. Conflitos e territorialidade no uso de recursos pesqueiros do Médio rio Negro. Encontro Nacional da ALNPPAS, 4. ANPPAS, Brasília. Anais. . . Brasília, pp. 78–91, 1.

Souza, L.A., Freitas, C.E.C., 2010. Fishing sustainability via inclusion of man in predator-prey models: a case study in Lago Preto, Manacapuru, Amazonas. Ecol. Modell. 221, 703–712.

Souza, L.A., 2003. Sustentabilidade Ecológica e Econômica da Pesca de Subsistência na Amazônia Central. Dissertação (Mestrado em Biologia Tropical e Recursos Naturais). Instituto de Pesquisas da Amazônia, Universidade Federal do Amazonas, Programa de Pós-Graduação em Biologia Tropical e Recursos Naturais, 139 pp.

Stave, K.A., 2002. Using system dynamics to improve public participation in environmental decisions. Syst. Dyn. Rev. 18 (2), 139–167.

Sterman, J., 2002. Business Dynamics: Systems Thinking and Modeling for a Complex World. Irwin/McGraw-Hill, New York, NY.

Storch, L.S., Glaser, S.M., Ye, H., Rosenberg, A.A., 2017. Stock assessment and end-to-end ecosystem models alter dynamics of fisheries data. PLoS One 1–11 (12), e0171644.

Thomé-Souza, M.J.F., Raseira, M.B., Ruffino, M.L., Silva, C.O., Batista, V.S., Barthem, R.B., Amaral, E.S.R., 2007. Estatística Pesqueira do Amazonas e Pará-2004. IBAMA/ProVárzea, 74 pp.

Verhulst, P.F., 1838. Notice sur la loi que la population suit dans son accroissement. Correspondence Mathematique et Physique 10, 113–121.
Walters, C.J., Christensen, V., Pauly, D., 1997. Structuring dynamic models of exploited ecosystems from trophic mass-balance assessments. Rev. Fish Biol. Fish. 7, 139–172.
Walters, C.J., Pauly, D., Christensen, V., Kitchell, J.F., 2000. Representing density dependent consequences of life history strategies in aquatic ecosystems: ECOSIM II. Ecosystems 3, 70–83.
Warner, M., 2000. Conflict management in community based natural resource projects: experiences from Fiji and Papua New Guinea. In: Working Paper No. 135. Overseas Development Institute, London, UK, pp. 1–40.
Youn, S., Taylor, W.W., Lynch, A.J., Cowx, I.G., Beard, T.D., Bartley, D., Wu, F., 2014. Inland capture fishery contributions to global food security and threats to their future. Glob. Food Secur. 3, 142–148.