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Protected areas as strategies for preserving vegetation cover in the vicinity of hydroelectric projects in the Brazilian Amazon

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Abstract

Background: There are several studies associating the construction of power plants to the increase in deforestation rates. However, there are no case studies analyzing deforestation near power plants, seeking to find a logic of how such deforestation occurs and attributing a statistical correlation with some factors that may mitigate or potentiate such deforestation. This study fills this gap on the scientific literature. Although it analyzes four cases, it is relevant given the lack of publications on this topic.

Methods: In this study, a comparative analysis of deforestation was conducted in the vicinity of four hydroelectric plant projects in the Amazon forest, aiming particularly to identify measures related to the creation of areas of restricted use, protected areas, and indigenous lands, as a way to minimize the predatory occupation around reservoirs.

Results: The results showed that there is a strong negative correlation between the extension of indigenous lands and protected areas and deforestation in the vicinity of the power plants analyzed, even when they are located in areas with a high level of human occupation. This study also revealed, by Pearson correlation analyses, that there are few pairs of variables whose correlations are weak or very weak. There are predominantly moderate, strong, and very strong correlations.

Conclusions: Thus, it is suggested that new hydroelectric plant projects in the Amazon should prioritize the creation of areas of restricted use and discourage occupation through settlements and opening of roads, as these variables were determinant for the level of degradation to the environment around the construction works analyzed.

Keywords: Deforestation, Protected areas, Indigenous lands, Energy, Hydroelectric plants, Amazon

Background

There are three major natural oases in the contemporary world: Antarctica, which is a space divided among the great powers; sea beds, which are very rich in mineral and plant life and not legally regulated; and the Amazon region, which is located within South American nation states, including Brazil [1].

The occupation of the Brazilian Amazon has intensified since the 1970s, allowing the use of a portion of that territory for the national economy. The role of the region in global capitalism is predominantly as a supplier of mineral primary commodities (iron ore, bauxite, manganese, zinc, copper, and lead), which are exported raw or processed into primary metals (aluminum ingots, iron, and steel alloys). They are high-energy products with a low added value that degrade the environment [2].

To make the existence of energy-intensive industries possible and to supply electricity to municipal centers, especially state capitals, large hydroelectric plants have been built. The construction of such power plants was accompanied by major environmental impacts, some of

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which cannot be avoided but rather mitigated or compensated.

There are several studies associating the construction of power plants to the increase in deforestation rates [3–14]. One of the most effective ways to offset impacts on the natural environment is the creation of areas of restricted use such as protected areas (PAs) and indigenous lands (ILs). Regarding PAs, resolutions 10 (of 1987) and 02 (of 1996) of the Brazilian Environment Council (CONAMA) established that the licensing of significant environmentally impacting construction works should have as a requirement the implementation of a public-domain protected area.

It is relevant to highlight that the energy production model in Brazil from the 1990s changed gradually and that large power plants, built mainly from 2000, such as Belo Monte, allocate most of their production to the regulated market. This reality is made possible by the existence of a large interconnected national energy system, one of the largest interconnected systems in the world. Thus, the energy produced integrates the system as a whole regardless of the final user or the geographic location.

The history of the construction of power plants in the Amazon shows that, in the 1970s and 1980s, there were many violations of rights of populations living near the construction works, mostly indigenous peoples. The Brazilian government, which was responsible for the construction and operation of these works, was also responsible for the loss of lands and resources of such populations, which, in most cases, was not followed by due compensation [15, 16].

Although there was an improvement in the legislation of the environmental sector in the last decades, power plants built in the Amazon during the first decades of the twenty-first century, mainly Belo Monte (Xingu river) and Santo Antônio e Jirau (Madeira river), are still lessons not learned regarding the development of such projects in the Amazon. This evidences the need for improvement in mitigating and compensatory measures for the populations hindered by these projects.

\It is important to note that institutions in Brazil (environmental and regulatory agencies), despite the environmental licensing process, propose constraints aimed at the wellbeing of the population in the vicinity of hydroelectric reservoirs; in general, these measures for environmental compensation and mitigation fail due to the lack of monitoring.

This study conducted a comparative analysis of soil use and occupation near four hydroelectric plants in the Brazilian Amazon forest built in 1970/1980 and the second decade of the twenty-first century. Particularly, it aimed to identify measures related to the creation of areas of restricted use, protected areas, and indigenous lands as a way to minimize the predatory occupation around reservoirs.

Methods

Study area

The hydroelectric power plants (HPPs) analyzed were Tucuruí (first stage construction between 1975 and 1984, and second between 1981 and 1989), Balbina (construction between 1981 and 1989), Samuel (construction between 1982 and 1989), and Belo Monte (its construction began in 2011, and it went into operation in 2016) (Fig. 1).

Data and methods

The structuring of the geographic database was made by the acquisition of data from institutions that centralize information specific to each study field. This information included the limits of protected areas (Chico Mendes Institute for Biodiversity Conservation, ICMBio), map database (Brazilian Institute of Geography and Statistics, IBGE), indigenous land limits (Brazilian Indigenous foundation, FUNAI), and Agrarian Settlement Projects (Brazilian of Colonization and Agrarian Reform, INCRA).

To estimate the extension of the region surrounding the reservoir, an analysis radius was used as a basis for this estimation [17–21].

In the case of Tucuruí HPP, these authors [22] estimated that its construction affected, with a greater intensity, a 150-km radius from the HPP axis. This resulted in an area of 90,000 km^2 for each reservoir. The analysis of the variables was performed within this spatial area.

This spatial area was also used in a more recent analysis conducted by other authors [10, 23]. The other three analyzed cases were similar to Tucuruí HPP, including the variables proximity to major highways and regions with an expanding occupation.

The criteria for the choice of the analyzed data (satellite images, etc.) were based on the beginning of the construction of each HPP. The year 2015 was chosen as a limit for the analysis. To analyze the surroundings of a project more appropriately, without the buildings, the first year analyzed was the one prior to the beginning of construction of buildings.

Regarding the quantification process of deforestation around the reservoirs, data previous to 2000 were used. A supervised classification was made using the nearest neighbor algorithm based on the spectral characteristics of the images. For the analysis after the year 2000, Deforestation Monitoring Project data from the Legal Amazon Satellite (PRODES), of the National Institute for Space Research (INPE), were used.

Projects analyzed, years considered, and the orbit-point of Landsat images are shown in Table 1.

Importantly, cloud cover conditions are also factors limiting the analysis. Because Landsat uses optical instruments, the weather conditions during the

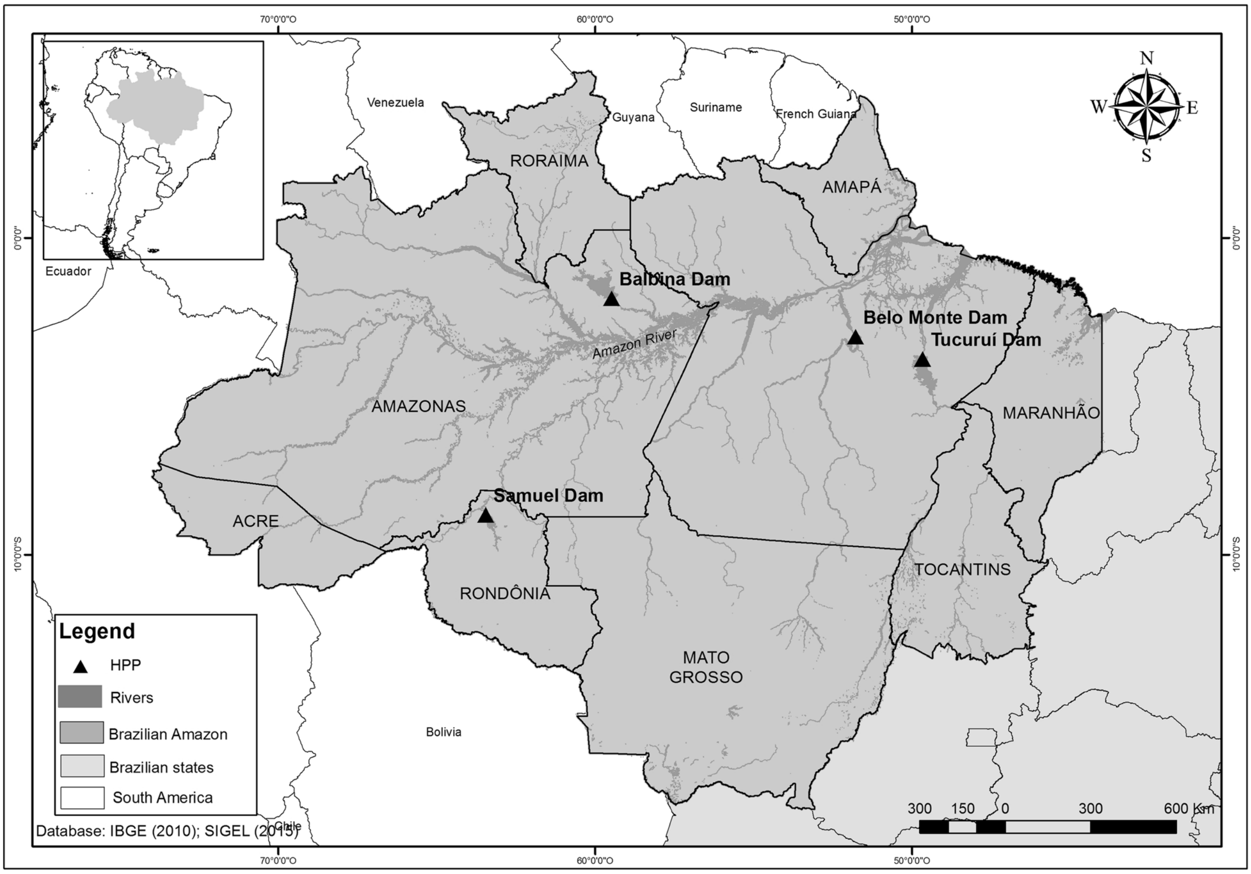

Fig. 1 Construction projects analyzed

Table 1 Analyzed projects, considered years, and orbit-point images

HPP	Years analyzed	Satellite/scenes
Tucuruí	1974	Landsat 1: 239/062/063/064; 240/062/063/064; 241/062/063/064
	2015	Landsat 8: 223/062/063/064; 224/062/063/064; 225/062/063/064
Balbina	1980	Landsat 2: 247/060/061/062; 248/060/061/062; 249/060/061/062
	2015	Landsat 8: 230/060/061/062; 231/060/061/062; 232/060/061/062
Samuel	1981	Landsat 2: 248/065/066/067; 249/065/066/067; 250/065/066/067
	2015	Landsat 8: 231/065/066/067; 232/065/066/067; 233/065/066/067
Belo Monte	2010	Landsat 5: 224/063; 225/061/062/063; 226/061/062/063
	2015	Landsat 8: 224/063; 225/061/062/063;226/061/062/063

capturing of the images may impair the clarity of information.

The classes of use and land cover were prepared based on the methodologies proposed in the literature [24, 25].

To analyze the correlation between the 12 variables (Table 2) involved in this study, an Excel spreadsheet, version 2010, was created containing the percentage values of each variable.

To prepare the Pearson correlation matrix, IBM SPSS Statistics 20 software was used. The data exported from the Excel spreadsheet were used. Thus, it was possible to determine the correlation coefficient and evaluate the degree of correlation between the variables.

The Pearson correlation coefficient is calculated using equation:

$$\rho = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2} \cdot \sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} = \frac{\operatorname{cov}(X,Y)}{\sqrt{\operatorname{var}(X) \cdot \operatorname{var}(Y)}},$$

where $x_1, x_2, \ldots, x_n$ and $y_1, y_2, \ldots, y_n$ are the measured values of both variables.

The $\bar{x} = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i$ and $\bar{y} = \frac{1}{n} \cdot \sum_{i=1}^{n} y_i$ are the arithmetic means for both variables.

Table 2 Variables analyzed

	Variables	Description
1	Accumulated deforestation in the vicinity of the HPP up to 2015	Considering a surrounding region of 150 km, forest loss was estimated up to the year 2015.
2	Percentage of protected areas surrounding the HPP up to 2015	One of the hypotheses of the article is that the protected areas help to preserve the forest—so the percentage of this typology area of restricted use around the HPP, which existed until 2015, was calculated.
3	Percentage of indigenous lands surrounding the HPP up to 2015	The hypothesis that indigenous lands help to preserve the vegetation cover was accepted—so the percentage of this typology area of restricted use around the HPP, which existed until 2015, was calculated.
4	Percentage of agrarian settlement projects surrounding the HPP up to 2015	Differently from the PAs and ILs, settlement projects do not have as a main goal the preservation of vegetation cover. These areas have as the main objective the colonization of areas by small farmers. So, it is important to know the influence of these areas near the HPP until 2015.
5	Percentage of deforestation accumulated in protected areas up to 2015	To analyze how much deforestation existed within the PAs, and to verify forest preservation in these areas, the percentage of deforestation within this typology was calculated up to 2015.
6	Percentage of deforestation accumulated in indigenous lands up to 2015	In order to analyze how much deforestation existed within the ILs, and to verify forest preservation in these areas, the percentage of deforestation within this typology was calculated up to 2015.
7	Percentage of deforestation accumulated in agrarian settlement projects up to 2015	In order to analyze how much deforestation existed within the SPs, and to verify forest preservation in these areas, the percentage of deforestation within this typology was calculated up to 2015.
8	Creation of protected areas directly related to the construction work	It has been found in the case studies analyzed that many PAs created around HPPs were unrelated to the enterprise. So, we opted to analyze only those that somehow had their creation related to HPP.
9	Extension of roads surrounding the hydroelectric up to 2015	Roads are related to the occupation of areas and to the access to forested areas, so it was important to know the extent of the roads around each HPPs analyzed until 2015.
10	Time (years) between the beginning of the construction and the creation of the first protected areas	The time of creation of the PAs around HPPs could be related to greater maintenance of forest cover.
11	Number of registered indigenous lands directly related to the project	With a protection status granted to the environment, the creation of indigenous lands has importance in the maintenance of forest cover.
12	Time (years) between the beginning of the construction and the approval of the first indigenous land	The time between the beginning of the construction of the HPP and the registration of the first ILs can be an important variable in the preservation of the forest.

The Pearson correlation coefficient measures the degree of linear correlation between two quantitative variables. It is a dimensional index with values between − 1 and 1 inclusively, which reflects the intensity of a linear relationship between two sets of data.

The classification used for correlation values (positive or negative) is as follows: very weak (0.0–0.19), weak (0.20–0.39), moderate (0.40–0.69), strong (0.70–0.89), and very strong (0.90–1.00) [26].

It is important to mention that, since the coefficient is designed from the linear adjustment, then the equation does not contain adjustment information; that is, it is composed only of the data.

An extensive research was also done in the existing literature (articles, books, and reports) on the subject in order to understand and analyze the results obtained.

Results

Tucuruí

By the year 1974, it was found that only 3% of the area surrounding the Tucuruí HPP was deforested. Although the presence of the Trans-Amazon highway was already relevant in the landscape, an early occupation occurred. The cover by water bodies was only 2% of the analyzed area (Fig. 2). The Tucuruí dam was closed in September 1984, causing the flooding of over 2400 km^2.

In the area of influence of the projects, one of the oldest protected areas in the region was established, but its creation was not directly linked to the project. The Biological Reserve of Tapirapé, 140 km upstream from the reservoir, was created in 1989 as a "buffer zone" for the mineral deposits of the Carajás Iron Project [27]. The Extractive Reserve Ipau-Anilzinho, 60 km downstream from the reservoir, was created in 2005 also without a direct relationship to the HPP. In total, there are 7028.22 km^2 of protected areas surrounding the Tucuruí HPP (Fig. 2).

The creation of PAs located within the Tucuruí reservoir limits only occurred in 2002. However, these units are restricted to the reservoir. Representative forest areas were not included because, in 2002, there were almost no surrounding forest areas for such an action.

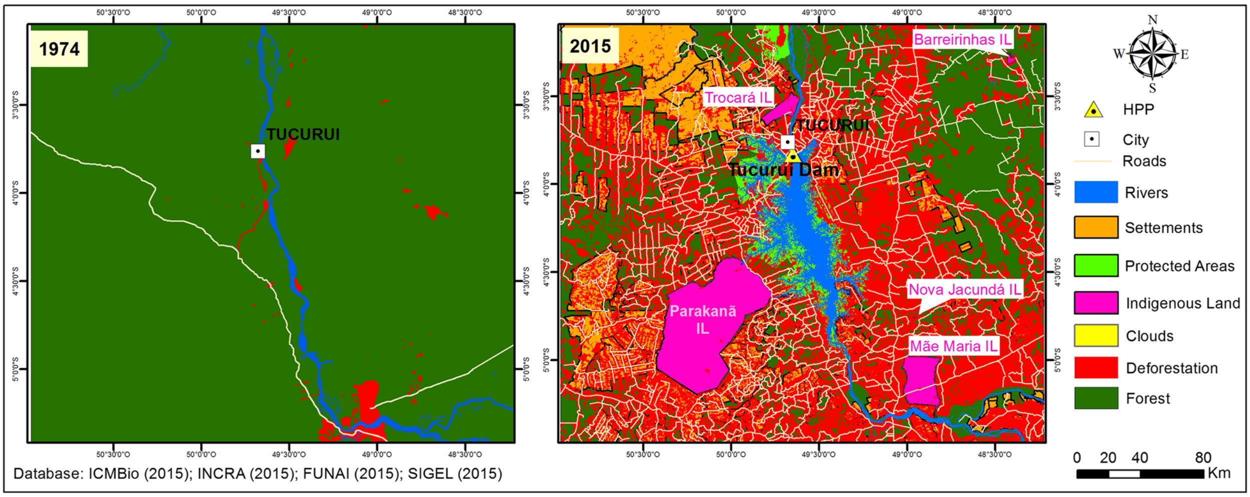

Fig. 2 Region of the Tucuruí HPP, in 1974, a year before the beginning of the construction of the HPP, and in 2015

In Tucuruí, due to roads and side-roads built in the vicinity of the lake, there was a dysfunctional occupation around it, leading to an excessive extraction of wood (especially the most profitable types of timber), triggering a generalized degradation process. In 1974, there were less than 1000 km of highways and roads in the area. In 2015, that number had increased to more than 13,000 km, showing how intense the appropriation of the territory was.

With regard to land use within protected areas, deforestation comprises about 27% of their territory. When all the 90,000 km^2, analyzed in 2015, are included in the calculation, the deforestation rate reaches 52%, considering 5% of the class "cloud cover," when it was not possible to obtain information on land use.

Different from protected areas, which are created due to more abstract factors such as landscape beauty or representativity of ecosystems, indigenous lands are created to preserve the rights of indigenous peoples over their lands, which constitute a costumary law prior to the creation of the state itself. This results from recognizing the historical fact that the Indians were the first inhabitants of Brazil [28]. In the case of Tucuruí, several indigenous groups, such as the Parakanã, Asurini, and Gavião Parkatêjê, lived in the area affected by the construction of the reservoir.

Considering the submerged area, 36% belonged to Parakanã Indians. In order to minimize the impacts on indigenous peoples, the Northern Brazil Power Plant company (Eletronorte), through an agreement with FUNAI [29], developed the "Parakanã Program," whose main purpose was to improve health, bilingual education, production support, and territorial protection. The implementation of this program caused growth of the indigenous population and the possibility of preserving an ancient culture. There were 257 Parakanã Indians shortly after the entry into operation of the HPP in 1986. The Eletronorte agreement [30] reached 1086 people, distributed in 15 villages, in 2015.

With an area of 351,000 ha, the Parakanã IL was demarcated and ratified in 1991 with support from Eletronorte. The indigenous territory keeps its original vegetation cover, despite strong pressures from lumber companies throughout the eastern Southeast Amazon. It is supported by the "Parakanã program" through a systematic monitoring of the limits and of the users of the Trans-Amazon Highway, which borders the indigenous land [30].

Other ILs existing in the study area are Trocara, Mãe Maria, Barreirinhas, and Nova Jacundá. Despite not having a direct relationship with the HPP, they helped keep the vegetation cover in their surroundings (Fig. 2).

Upon comparatively analyzing the various types of areas surrounding the Tucuruí HPP, it is observed that the vegetation is more preserved in ILs, with only 1% of deforestation. This index is lower than that observed in PAs (38%) for the surrounding environment as a whole (52%). The highest deforestation rate was found inside INCRA settlement projects (SPs), reaching 57%. In the analyzed area, according to the INCRA database, there are 241 settlement projects, totaling 23,100 km^2 or 25% of the land considered as surrounding lands.

Balbina

The construction of the Balbina hydroelectric power plant began in 1981, and it was inaugurated in 1989. It formed a lake of approximately 2360 km^2, and the installed capacity is 250 MW. The flat topography and the small size of the Uatumã river basin resulted in low energy production in relation to the flooded area. Balbina sacrifices 35 times more forest per megawatt of installed generation capacity than the Tucuruí HPP [31]).

The occupation of the region was accelerated from the 1960s and 1970s with the advent of the NIP (National Integration Plan) and the development of policies for the region, especially the construction of the BR-174 highway in the 1970s. The occupation of northern Amazonas was based on three projects: the construction of the BR-174 (1974–1977), the Pitinga project (cassiterite extraction), and the construction of the Balbina HPP [32].

It appears that only 1% of the analysis area was deforested in 1980. Despite the strong presence of the BR-174, the occupation was at an early stage. The class "rivers" covered 2% of the analyzed area (Fig. 3).

In the time of the environmental studies, a great number of islands emerged after the reservoir was considered as an environmental advantage because it represented an environmental preservation method that was flooded [27]. However, the islands did not present satisfactory ecological conditions to house animals and plants, because when a forest is divided into fragments, many species of animals and plants are lost as the small areas of isolated forests degrade [33].

One of the most common consequences of forest flooding by hydroelectric reservoirs is the production of hydrogen sulphide (H_2S). Before Balbina, this consequence had already been observed for the Brokopondo HPP (Suriname) and Curuá-Una (Brazil, Pará) [34, 35].

During the 1980s, in order to minimize and mitigate the impacts of the construction of the Balbina HPP, ecological and environmental control studies were conducted by Eletronorte in the area of influence of the power plant. Such studies were mainly conducted by the National Institute of Amazonian Research (INPA) [36]. The first PA of the region was established in 1990 by the Brazilian Environmental Agency (IBAMA). The Biological Reserve of Uatumã, on the left bank of the reservoir, protected representative samples of the ecosystems of the basins of the Uatumã and Jatapu rivers.

Besides the Biological Reserve, there are two other direct-use protected areas in the region of influence of the Balbina reservoir: the Environmental Protection Area of Presidente Figueiredo (1990) and the Sustainable Development Reserve of Uatuamã (2004). Other areas were created in the surroundings, although not directly related to the power plant. The total area with a legal protection in the form of protected areas totals 28,995.03 km^2 (Fig. 3).

There was a moderate growth of roads in Balbina, different from what occurred in Tucuruí. The roads totaled approximately 1100 km in 1980, reaching approximately 3000 km in 2015. This was mainly due to the poor ramification of the Manaus-Boa Vista highway (BR - 174) and the presence of areas of restricted use.

Deforestation in the area "surrounding" Balbina has a very low road presence according to data from PRODES/INPE for 2015 [37], both within PAs and outside them. The percentage of forest lost by deforestation is only 2%. Despite the significant cloud cover observed during the analysis (11% on average and 16% in PAs), the vegetation has been preserved despite the aforementioned pressures.

Concerning indigenous lands, in order to compensate the Waimiri-Atroari Indians, an area of 25,859 km^2 stretching from the north of the Amazonas to the south of Roraima was delimited by Decree no. 97,837/1989. FUNAI estimates that the Indian population was between 500 and 1000 people in the 1970s. Due to the contact with the non-Indian population, opening of roads, and mining, the decrease in the population

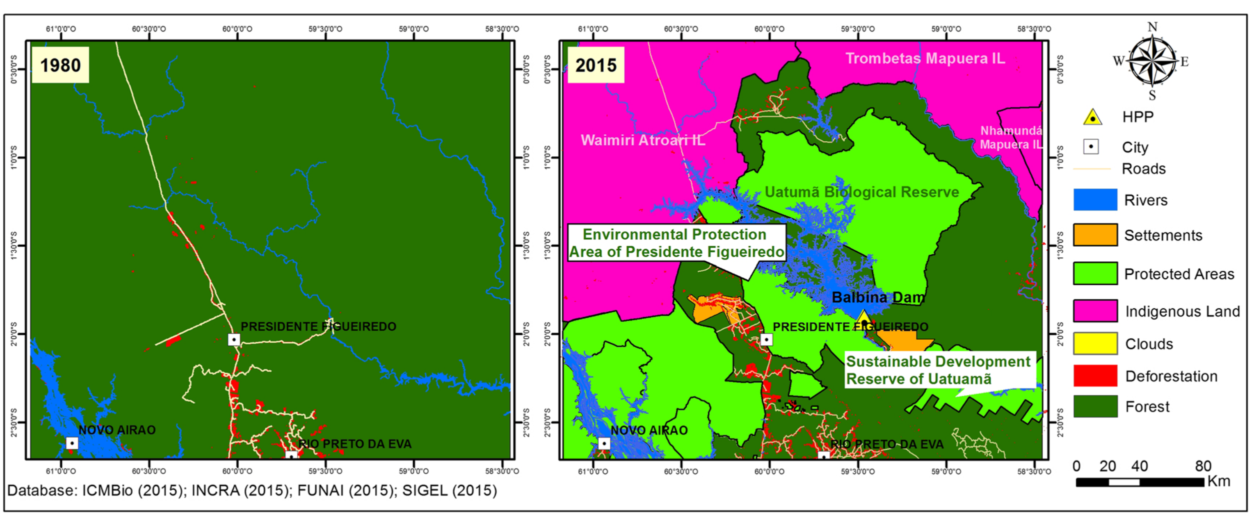

Fig. 3 Region of the Balbina HPP, in 1980, a year before the beginning of the construction of the HPP, and in 2015

reached a critical level in 1988, when only 374 people were recorded.

The Waimiri-Atroari Program was implemented in 1987 to offset the impacts of the HPP. It proposed an indigenous policy for this area and actions in health, education, environment, support for production, monitoring of boundaries, preservation of culture, documentation, and memory. With this agreement, the IL was demarcated and ratified in 1989 [19]. The current population of the Waimiri-Atroaris is 1839 inhabitants, distributed into 40 villages, in 2015 [38].

Other ILs existing in the study area are Nhamundá/Mapuera, Trombetas/Mapuera, and the Piriti IL. The latter is still under the recognition and approval process (Fig. 3).

The state of plant cover preservation in the vicinity of Balbina ILs is excellent. In an analysis using PRODES/INPE data from 2015, it was found that less than 1% of such areas are classified as deforested. Comparing the areas, there is an average of 7% of deforestation within settlements, 3% in the surrounding vegetation in general, 2% in PAs, and 3% in ILs.

In the analyzed area, according to the INCRA database, there are 12 settlement projects, totaling 1237 km^2 or 1.3% of land considered as surrounding lands. The settlements in the region were created between 1987 and 2014.

Samuel HPP

The hydroelectric power plant of Samuel was built in the Jamari River, 96 km from the confluence with the Madeira River and approximately 52 km from Porto Velho. The reservoir extends over an area of approximately 560 km^2 [39]. The construction of the HPP began in March 1982. The Eletronorte plans were that, by 1990, all 216 MW, distributed into five turbines, should have been in operation. However, due to increased costs and delays in disbursement, the first turbine started operating only in 1989.

The hydroelectric power plant of Samuel was built in an area that, in the 1980s, presented one of the highest deforestation rates in the world [40]. When the construction of the power plant began, the population of Rondônia was growing exponentially at a rate of 16% per year, and deforested areas were expanding by over 29% per year [41].

In 1981, a year before the beginning of the construction works of the Samuel HPP, there were already many deforestation points along the highways and the Jamari River. In 1981, about 5% of the area was deforested. There is a strong presence of highways and an accelerated process of occupation along them. The class "rivers" covered 1% of the analyzed area (Fig. 4).

The spread of roads in a "herringbone" formation characterized the occupation of Rondônia state. Before the construction of the Samuel HPP, there were approximately 3700 km of roads in the vicinity. According to the IBGE, that number was close to 8000 km in 2015.

The first PA surrounding the power plant of Samuel was the Jamari National Forest [42], established in 1984. Its origin is connected to the process of colonization of the region. Another unit was established in 1987, the Ecological Station of Samuel, on the right bank of the reservoir. The choice of the area, as well as its size, was made taking into account the proximity to the reservoir, the granting of the area to Eletronorte, the possibility of including vacant lands, the representativity in the ecosystem area flooded by the Samuel reservoir, and the possibility of maintaining a more effectively conserved area due to the continuity with the Jamari National Forest.

Despite receiving financial support from Eletronorte, the Ecological Station of Samuel does not have any management plan or operating advisory board. Eletronorte does not offer the systematic support necessary for the protection of the area [43].

In 2013, the State Department of Environmental Development of Rondônia—SEDAM and Eletronorte signed technical cooperation agreement no. 528/2013, without any transfer of funds. Its objective was the mutual cooperation of the participants for the implementation of protection and conservation actions for the Ecological Station of Samuel. The details, resources, responsibilities of the parties, objectives, and implementation stages of this agreement are set out in the work plan, which is part of the agreement. In the SEDAM website, the unit management plan is under preparation along with a partnership with Eletronorte [44].

Throughout the analysis area, 39 protected areas were found (Fig. 4). The majority of them (32) have a sustainable use and 7 are fully protected, totaling 29,913.06 km^2.

A comparative analysis of deforestation in the HPP surrounding shows that areas of restricted use helped to keep the vegetation cover. Even with all the historical pressure that the region suffers, it appears that only 5% of vegetation cover has been lost within the protected areas. The existence of protected areas in northern Roraima and southern Amazonas underlies the importance of restraining the spread of the "arc of deforestation." When the general surrounding area is considered, this number rises to 32%.

No indigenous lands were flooded by the Samuel power plant. However, after the construction of the dam, impacts were felt by the Uru-Eu-Uau-Uau tribe, which inhabits the headwaters of the Jamari River, approximately 160 km downstream within the reservoir. The change in the migration of fish and the contribution to attracting an additional population to Rondônia led to an increasing pressure on indigenous lands [45]. The proximity of the indigenous Karitiana area to the reservoir (70 km downstream) was considered as a threat to the Karipuna tribe, which had a population of only 175 individuals [46].

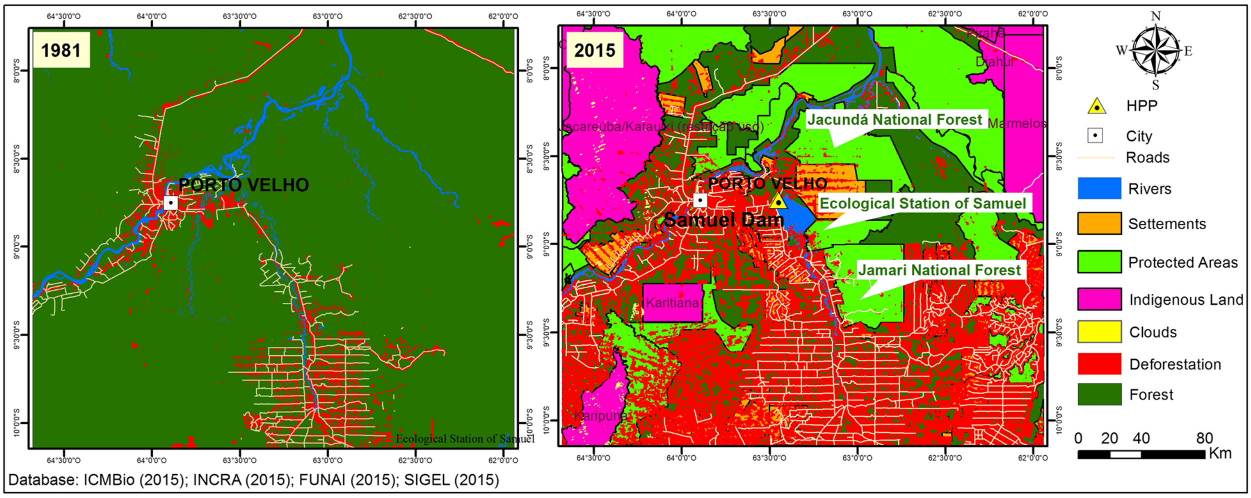

Fig. 4 Region of the Samuel HPP, in 1981, a year before the beginning of the construction of the HPP, and in 2015

In the surrounding radius analyzed, according to FUNAI (2015) [47], nine ILs at different stages of creation extended over 14,286.98 km^2. No IL was created together with the HPP, and the nearest indigenous land (60 km) is the Karitiana (Fig. 4).

With regard to land use in these areas, it was observed that deforestation was only 2% in 2015, an index lower than that of other PAs (5%). The increased rate of deforestation occurred in INCRA settlements, reaching 57%. In the analyzed area, according to the INCRA database, there are 80 settlement projects, totaling 12,618 km^2 or 14% of land considered as surrounding lands.

Belo Monte

One of the most controversial infrastructure projects in the Amazon is the power plant of Belo Monte. Its initial design dates back to the 1970s. This construction work has been marked by controversy ever since. Belo Monte is considered one of the most environmentally controversial projects and the one with most interference from the Judiciary in the history of the Brazilian Amazon.

The initial project was marked by conflicts with indigenous peoples of the Xingu river because there was a forecast of flooding of large areas historically occupied by these peoples. An NGO and several other institutions defending the rights of forest peoples were involved in this issue. They went against the government's interests in the development of the project, mainly in the beginning of the 2000s. This project was considered as a priority for the energy production Brazil needed for its economic growth [48].

The Environmental Impact Assessment (EIA) was delivered to IBAMA in July 2009. In February 2010, the work obtained the Preliminary License. The beginning of the construction dates from June 2011, when the Installation License was obtained. The filling of the reservoir began in February 2016, and the first turbine began operating in April of that same year.

Throughout its development, the hydroelectric project of Belo Monte was deeply modified in order to limit the impacts that the project could cause to the environment and the population of the region. The flooded area was reduced by 60% compared to the initial project, resulting in a reservoir of 516 km^2 of flooded area; about 228 km^2 (44%) correspond to the original bed of the river [49].

In 2010, protected areas covered 13,156.63 km^2 and were concentrated in the northern part of the area analyzed. The indigenous lands stretched south of the project with an area of 19,393.22 km^2.

The areas surrounding Belo Monte have significant historical deforestation rates, which started much earlier than the construction work and are mainly related to agricultural activities and colonization projects. The rate of deforestation in the area in 2010, a year before the beginning of the construction of the HPP, was already 19%, according to data from PRODES/INPE.

In 2010, deforestation was 17,198.11 km^2, with an increase of 1771.55 km^2 between 2011 and 2015. Thus, total deforestation reached almost 19,000 km^2. Between 2011 and 2015, the increase in deforestation was slightly higher than 10% (Fig. 5).

In the vicinity of hydropower, the nearest protected area is the Verde para Sempre Extractive Reserve, located 70 km downstream from the HPP. Another PA is the National Forest of Caxiuanã, nearly 100 km downstream from the HPP.

In 2010, the intense occupation of the region in which the hydroelectric plant would be built and the absence of protected areas in its vicinity were important factors taken into consideration during the licensing process.

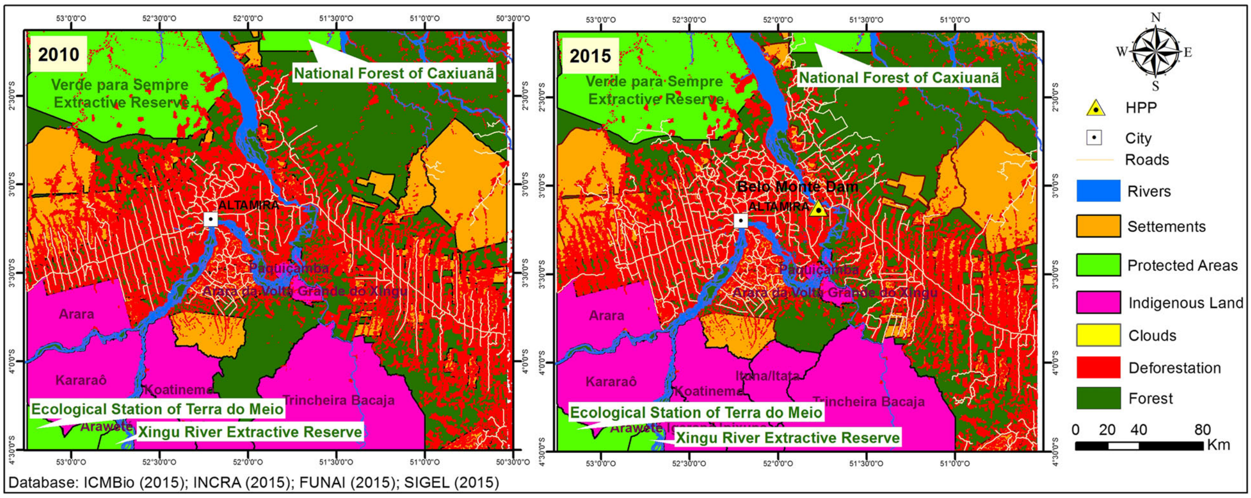

Fig. 5 Region of the Belo Monte HPP, in 2010, a year before the beginning of the construction of the HPP, and in 2015

Other PAs, such as the Ecological Station of Terra do Meio and the Xingu River Extractive Reserve, are more than 170 km away from the HPP (Fig. 5). The lack of protected areas in the surrounding environment was an aggravating factor for estimates of indirect deforestation caused by the construction works.

In this regard, a major concern during the Belo Monte licensing process was the risk of deforestation, which could be increased. In that sense, to facilitate the actions of the basic environmental plan of the HPP, a report was prepared in 2010, which sought to meet the demands of the federal licensing agency regarding the estimates of deforestation risks associated with the implementation of Belo Monte. One of the most urgent findings of the study was the need to establish protected areas around the power plant.

Because of this, studies that supported the licensing of the HPP proposed three areas with an urgent creation of protected areas. The first is limited to indigenous land of Arara da Volta Grande and consists of a polygon with approximately 80,000 ha of forest in a good conservation condition. The second potential area is located south of the Indirect Influence Area of the Belo Monte HPP, between the indigenous lands Koatinemo and Trincheira Bacajá (unit 2), with approximately 200,000 ha. There are also well-preserved forests, which could, along with the aforementioned indigenous lands, form a continuous portion of forest with about 1.6 million hectares.

However, on January 11, 2011, because of the publication of the Ordinance no. 38, FUNAI reserved part of unit 2 to the creation of the Ituna/Itata indigenous land, which has approximately 137,000 ha.

There was also the proposition of a third protected area that would preserve the ecosystems of the Xingu River. In this regard, the importance of conserving the river plains and other streams in the region was stressed because they are key sites for fish breeding, food and reproduction of aquatic turtles, and a maintenance region for the primary productivity of the system. However, although included in the environmental impact study and in the environmental basic plan, no protected areas were created up to the HPP's entry into operation in April 2016.

On the other hand, the government of the state of Pará, through Decree no. 1566/2016, created in 2016 two protected areas within the area of influence of Belo Monte: The Tabuleiro do Embaúbal Wildlife Refuge (WR) (4034 ha) and the Sustainable Development Reserve (SDR) of Vitória de Souzel (22,957 ha).

Comparison among HPPs and the variables analyzed

To analyze the correlation between the implementation of hydroelectric power plants and their influence on the deforestation process within their influence area, the Pearson correlation method was applied to the selected variables.

Table 3 shows the values of the variables and the correlation matrix between the variables of the hydroelectric power plants of Tucuruí, Balbina, Samuel, and Belo Monte. Their values discriminate the Pearson correlation between pairs of variables.

It can be observed that, without exception, all variables present correlation coefficients with absolute values higher than 0.7 for at least one of the variables, i.e., the correlations among the variables studied are predominantly strong.

Thus, this study tried to show if one or more variables could have any influence on deforestation. Observing Table 4, it is noticed that the variable extension of highways has a very strong positive correlation ($r = 0.979$) with the variable deforestation in the surroundings,

Table 3 Variables of the four hydroelectric power plants analyzed

Variables	Tucuruí	Balbina	Samuel	Belo Monte
Accumulated deforestation (%) in the vicinity of the HPP up to 2015	52	2	32	20
Percentage of PAs surrounding the HPP up to 2015 (%)	8.4	32.5	33.2	14.6
Percentage of ILs surrounding the HPP up to 2015 (%)	4.8	33.9	15.8	23
Percentage of SPs surrounding the HPP up to 2015 (%)	25.6	3.9	14	16.3
Accumulated deforestation in PAs (%) up to 2015	25	2	2	3
Accumulated deforestation in ILs (%) up to 2015	1	< 1	2	< 1
Accumulated deforestation in SPs (%) up to 2015	55	7	57	30
Extension of roads surrounding the HPPs up to 2015 (km)	13,990	2903	7547	5791
Creation of protected areas directly related to the construction work	3	3	1	2
Time (years) between the beginning of the construction and the creation of the first protected area	27	9	6	5
Number of approved indigenous lands directly related to the project	2	1	0	1
Time (years) between the beginning of the construction and the approval of the first indigenous land	16	8	–	4

which may be an indication that the greater the extension of a highway, the greater the impact it has on the studied environment.

Another variable that presented a very strong positive correlation with the deforestation variable in the environment was the percentage of SPs ($r = 0.941$), which can be interpreted as the greater the extension of settlement projects, the greater the deforestation caused.

On the other hand, it was noted that the variable IL percentage has a perfect inverse correlation with the variable deforestation in the environment ($r = -1000$), indicating that the greater the presence of indigenous lands, the smaller would be deforestation.

In order to obtain a visualization of the results obtained above, a data dispersion matrix was created for the pairs of variables with higher correlation, shown in Fig. 6. The matrix corroborates the analyses, because it is possible to note the relationships previously described.

Considering the negative correlation results, the need for the creation of indigenous lands as a way to curb the proliferation of roads, which are clearly one of the biggest vectors of deforestation, can be inferred.

When analyzing the strong negative correlation of the percentage of protected areas within the area analyzed for each of the reservoirs, it is found that the greater the extent of such smaller units, the greater the chances of deforestation within those areas.

It can be inferred by the degree of positive correlation that when the value of one variable increases, the value of the other also increases. In this context, there was a very strong and positive correlation between variables %SPs_2015 and %Def_2015 ($r = 0.941$), %Def_SPs_2015 and %Def_2015 ($r = 0.907$), extension of roads and %Def_2015 ($r = 0.979$), extension of roads and %SPs_2015 ($r = 0.936$), extension of roads and %Def_PAs_2015 ($r = 0.915$), Time_Constr_1stPA and %Def_PAs_2015 ($r = 0.981$), Time_Constr_Approv_ILs and Time_Constr_1stPA ($r = 0.923$), and Time_Constr_Approv_ILs and Approval_ILs ($r = 0.923$).

Thus, for the surroundings of the reservoirs analyzed, it can be observed that total accumulated deforestation up to 2015 has a very strong relation with extension of settlement projects, and total accumulated deforestation with that observed within the project settlements. The extension of roads is also highly correlated with deforestation, as well as with the time elapsed between the beginning of the construction of the power plants and the approval of the first indigenous land.

Discussion

The literature is vast in showing that there is a stimulus to deforestation activities within hydroelectric power plant areas [4–7, 9, 22, 50, 51].

The main issue is the difficulty in identifying which part of this deforestation is directly or indirectly related to the construction work.

In most large projects in the Amazon region, the measures for the evaluation and minimization or neutralization of the impacts arise after the decisions have already been made, when there is no possibility of changing the project. Such large projects of regional development, in addition to the direct effects, cause indirect effects related mainly to the demographic growth and stimuli to activities such as agriculture and livestock. In many cases, these activities are carried out without complying with the current legislation, causing a pressure on spaces little inhabited or empty, as well as on other areas of restricted use such as indigenous lands and conservation units. These secondary effects sometimes are not taken into account in the planning of large projects, which hinders mitigating actions [1, 52–56].

However, there are mitigating actions, such as the creation of conservation areas, notably in the form of protected areas and indigenous lands.

Table 4 Correlation matrix between the variables of Tucuruí, Balbina, Samuel, and Belo Monte HPPs

Correlation matrix	% Def_2015	% PAs_2015	% ILs_2015	% SPs_2015	% Def_PAs_2015	% Def_ILs_2015	% Def_SPs_2015	Extension of roads	Creation_PAs	Time_Constr_1stPA	Approval_Ils	Time_Constr_Approv_Ils
% Def_2015	1	–	–	–	–	–	–	–	–	–	–	–
% PAs_2015	− 0.623	1	–	–	–	–	–	–	–	–	–	–
% ILs_2015	*− 1.000*	0.614	1	–	–	–	–	–	–	–	–	–
% SPs_2015	*0.941*	*− 0.837*	*− 0.940*	1	–	–	–	–	–	–	–	–
% Def_PAs_2015	*0.812*	*− 0.757*	*− 0.796*	*0.812*	1	–	–	–	–	–	–	–
% Def_ILs_2015	0.175	0.584	− 0.195	− 0.071	− 0.353	1	–	–	–	–	–	–
% Def_SPs_2015	*0.907*	− 0.319	*− 0.917*	*0.784*	0.499	0.558	1	–	–	–	–	–
Extension of roads	*0.979*	− 0.696	*− 0.973*	*0.936*	*0.915*	− 0.002	*0.804*	1	–	–	–	–
Creation_PAs	− 0.075	− 0.400	0.100	0.022	0.522	*− 0.870*	− 0.476	0.133	1	–	–	–
Time_Constr_1stPA	*0.721*	− 0.644	*− 0.703*	0.686	*0.981*	− 0.372	0.396	*0.846*	0.616	1	–	–
Approval_Ils	0.389	*− 0.804*	− 0.367	0.531	*0.828*	*− 0.817*	− 0.035	0.560	*0.853*	*0.832*	1	–
Time_Constr_Approv_Ils	0.432	− 0.652	− 0.409	0.479	*0.878*	− 0.683	0.027	0.609	*0.866*	*0.923*	*0.956*	1

%Def_2015—accumulated deforestation surrounding the HPP up to 2015
%PAs_2015—percentage of PAs surrounding the HPP up to 2015
%ILs_2015—percentage of ILs surrounding the HPP up to 2015
%SPs_2015—percentage of SPs surrounding the HPP up to 2015
%Def_PAs_2015—accumulated deforestation in protected areas up to 2015
%Def_ILs_2015—accumulated deforestation in ILs up to 2015
%Def_SPs_2015—accumulated deforestation in SPs up to 2015
Extension of roads—extension of roads surrounding the HPP up to 2015
Creation_PAs—creation of protected areas directly related with the hydroelectric power plants
Time_Constr_1stPA—time (years) between the beginning of the construction of the power plants and the creation of the first protected area
Approval_ILs—registered indigenous lands directly related to the project
Time_Constr_Approv_ILs—time (years) between the beginning of the construction of the power plants and the approval of the first indigenous land
More significant correlations are highlighted in italics

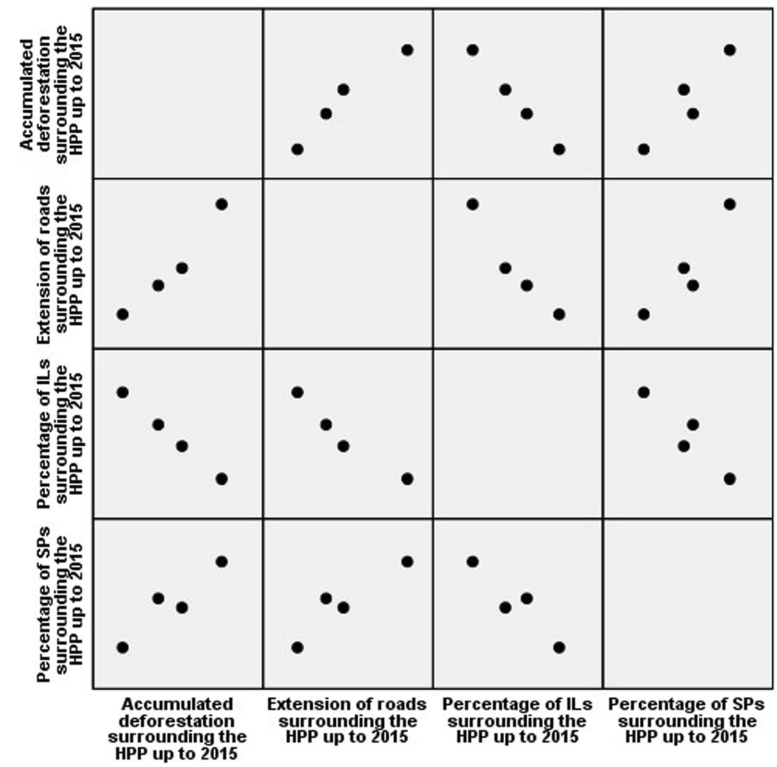

Fig. 6 Dispersion matrix of the following variables: deforestation in the environment, extension of highways, percentage of ILs, and percentage of SPs up to 2015

Some procedures to mitigate the impacts, such as the simple rescue of animals or plant specimens before filling the reservoir, are not considered effective measures because, generally, the damming results in the transfer or in the migration of animals to already occupied areas, causing a temporary overpopulation and a stress for the entire system. Such populations could decrease fast in the following years if there is no strict control of hunting and the protection of natural habitats around the dams [8].

A way to curb environmental degradation, the creation of protected areas, not only isolated units such as “islands” [57], but also a more integrated unit, as is the case of the association between different areas of restricted use, such as protected areas and continuous indigenous lands, as was proposed during the licensing studies of Belo Monte. The authors proposed the establishment of zones that, integrating ecological, economic, and socio-cultural objectives, sought to promote the sustainable development of large territories.

The existence of various types of protected areas may significantly reduce the speed of deforestation, thereby reducing the probability that any given hectare of forest will undergo a transformation from forests into any other type of land use [58].

Deforestation analysis in three sections of the Trans-Amazon highway in the state of Pará, showed that the extent of deforestation in the analyzed sections is directly related to the proportion of protected areas. The first section, with 12.9% of deforested area, had about 22.5% of its area inside protected areas and indigenous lands. However, the third section, the most deforested (51.2%), has a small 2.7% area represented by two indigenous lands [59].

The absence of restricted areas such as indigenous lands and protected areas contributed to the current deforestation situation observed in the vicinity of the hydroelectric power plants analyzed. In the case of Tucuruí and Samuel HPP, this deforestation was boosted because the construction of the plants was located in a settlement expansion area, with strong anthropic pressure resulting from the construction of roads, activities related to agriculture, and the creation of settlements close to major highways. Because of this dynamic, if both areas had not been used as a reservoir, there would probably be a landscape dominated by degraded pastures such as in neighboring areas.

Concerning indigenous lands, it was found that lands that received funds and support as a compensation for the impacts of the power plants are those in a better state of preservation, as is the case of the Parakanã IL, close to the Tucuruí HPP. The support for the creation of indigenous lands, besides correcting any historical debts regarding the indigenous population, also helps to conserve vegetation around the construction work.

In most of the cases, there was a proliferation of roads after the creation of the reservoir. Several studies show that the implementation of roads is a major cause of deforestation in the Amazon [60–63].

A new road can be the precursor to the intensification of economic activities such as agriculture, livestock, mining, power generation works, timber smuggling, speculation, and impacts on local people [64]. The highway becomes the main axis of secondary roads, extensions and rural roads following a herringbone scheme [65].

An aggravating factor in the analysis of the areas surrounding hydroelectric power plants was the stimulus to immigration and fixation of people through settlement projects. Many publications [66–70] described the effects of settlements on the context of deforestation in the Amazon. The data show that the diagnosis of deforestation performed in settlements have played a decisive role in forest degradation.

Authors [68] described that, from the total deforestation occurred in the Legal Amazon up to 2013 (758,638 km^2), 21% (161,833 km^2) occurred within rural settlements. The settlements in the Amazon resulting from agrarian reform, although they occupy only 5.3% of the biome, accounted for 13.5% of all deforestation in the region. In the surroundings of the projects analyzed, these numbers are close to those found for Tucuruí and Belo Monte HPP. In Tucuruí, the percentage of settlements is 14%, but the deforestation contribution is 25%. In Belo Monte, the numbers are similar [70]. Although covering approximately 16% of the area, it accounts for 23% of all deforestation in surrounding areas.

According to the data presented for the vicinity of the analyzed HPPs, ILs had the lowest deforestation rates among the analyzed typologies. This rate ranged between less than 1% in Balbina and Belo Monte and 2% in ILs surrounding the Samuel HPP.

Pearson's correlation analysis showed that there are few pairs of variables whose correlation is weak or very weak, with moderate to strong correlations or very strong.

The results of strong and positive correlations evidence the important relationship between the approval of the first PA and accumulated deforestation: the higher the number of years, the higher the deforestation percentage around the reservoir. A strong correlation between the extension of roads and the time for the approval of the first PA was also observed. This protected area acts as a barrier to the construction of roads. On the other hand, the extension of roads is strongly related to the deforestation observed within settlement projects.

It is worth mentioning that the amount of data makes the study limited; from the statistical point of view, the small number of projects can increase the bias of the analyses, but the study sample is not insignificant. It can be considered a descriptive analysis and the beginning for further investigation.

Conclusions

It is not possible to avoid comparing local development actions planned for the region with the history of occupation of the surroundings of the first large power plant in the region, the Tucuruí HPP.

Although current development planning is based on a more positive logic with regard to sustainability, the tendency for the establishment of a disordered occupation process, with a strong pressure on the environment, such as the case of Tucuruí and Samuel HPP, is more than a warning sign.

The strategy adopted by the government at the time of the opening of roads and the occupation of the surrounding area was extremely detrimental to the maintenance of the vegetation cover, leading to further deforestation. Together with such policies, the prioritization of the establishment of areas of restricted use, such as protected areas and indigenous lands, boosted the negative impacts on the native vegetation.

When observing that the most preserved area among the analyzed surrounding environments is Balbina HPP, it appears that some features have contributed to this, in particular:

a) A large presence of protected areas and indigenous lands
b) Low incentive for immigration with the creation of few settlement projects
c) Reduced numbers of roads and other access routes
d) Isolation of the region in relation to more intense occupations in the Amazon
e) Support from the company responsible for building the HPP regarding the demarcation of indigenous lands and the implementation of protected areas

It is worth mentioning that, although relevant results were obtained, the Programa Waimiri-Atroari and Parakanã, at the time their execution began, were widely criticized and seen as paternalist and culturally inadequate. In addition, it is important to note the influence of groups outside the discussion and implementation of the Convention of the International Labor Organization (ILO) on Indigenous and Tribal Peoples (1989), which were important factors for power plants to implement these programs.

The study concluded that the extent of deforestation in the analyzed cases is closely linked to four factors:

1) Extension of protected area
2) Extension of indigenous lands

3) Extension of settlement areas
4) Extension of roads surrounding the HPPs

This study also revealed, by Pearson correlation analysis, that there are few pairs of variables whose correlation is weak or very weak. There are predominantly moderate, strong, and very strong correlations.

Thus, when analyzing the data generated by this work, it is possible to verify that one of the greatest deforestation and occupation factors around the hydroelectric power plants is the presence of settlement projects. Thus, they should be avoided in areas under the influence of HPPs.

Therefore, an increase in incentives for the creation and implementation of protected areas and indigenous lands is suggested. The creation of settlements and roads providing access to green areas in good conditions must be discouraged. Time of creation of protected areas is also a variable with a strong correlation. As soon as these areas are created, there is lower deforestation in the vicinity of the analyzed construction works.

Upon comparing the time of creation of the analyzed projects, there was a decrease in the time between the beginning of the construction work and the creation of the first protected area and indigenous land. In the latter case, it is possible to observe that the time of the establishment of the first area was respectively 4 and 5 years, which leads the present authors to state that a higher priority should be given to the creation of such areas.

It is important to consider that, although analyzed by environmental studies and providing conditions for obtaining environmental licenses, the creation of areas of restricted use should be procedurally faster to avoid harmful activities prior to the full establishment of the area and/or activities which may jeopardize the preservation of vegetation diversity and coverage, as was the case of Tucuruí.

Abbreviations

CONAMA: Brazilian Environment Council; EIA: Environmental Impact Assessment; Eletronorte: Northern Brazil Power Plant company; FUNAI: Brazilian Indigenous foundation; HPPs: Hydroelectric power plants; IBAMA: Brazilian Environmental Agency; IBGE: Brazilian Institute of Geography and Statistics; ICMBio: Chico Mendes Institute for Biodiversity Conservation; IL: Indigenous land; INCRA: Brazilian of Colonization and Agrarian Reform; INPA: National Institute of Amazonian Research; INPE: National Institute for Space Research; PA: Protected area; PRODES: Deforestation Monitoring Project data from the Legal Amazon Satellite; SEDAM: State Department of Environmental Development of Rondônia; SPs: Settlement projects

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Availability of data and materials

Data scope and type	Database
Deforestation	http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes
Boundaries of indigenous land	http://mapas2.funai.gov.br/portal_mapas/kml/ti_sirgas2000.kml
Boundaries of protected areas	http://www.icmbio.gov.br/portal/images/stories/servicos/geoprocessamento/DCOL/dados_tabulares/Metadados/metadados_jan_2017.zip

Authors' contributions

OMdSJ idealized the theme of the research and was responsible for about 60% of the writing of the article. MAdS wrote about 20% of the article and revised the text. CFS wrote about 10% and revised the text. JMAG reviewed the statistics, and JPP performed the statistical analysis of the article. JMAG and JPP contributed the remaining 10% of the writing of the text. All authors read and approved the final manuscript.

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