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Environmental vulnerability assessment of Brazilian Amazon Indigenous Lands

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ABSTRACT

Amazonian Indigenous Lands (ILs) are human-environment systems facing a multitude of environmental threats. Yet, the resulting vulnerability of these systems are to date unknown. We adopt the theoretical vulnerability framework of the IPCC to assess the environmental vulnerability of Brazilian Amazon ILs for two periods (2001–2010 and 2011–2019) and overall (2001–2019). Vulnerability is deemed a function of exposure (EX), sensitivity (SE) and adaptive capacity (AC) of a system to threats. Sensitivity (threats within IL) and exposure (threats in IL's buffer zones) indicators are changes in forest cover, economic activities, and road access, quantified using data of deforestation, forest degradation, land-use, fire, roads and mining. Adaptive capacity indicators represent Indigenous self-organization, education and access to knowledge, land ownership, external incomes, and institutional arrangement. We find a concentration of ILs with high vulnerability in the Arc of Deforestation and South, and advancing in Pará and Roraima states. A strong relationship (Spearman r = 0.79) between EX and SE indicates the strong pressure exerted by external processes. An increase in EX (73.9% of the ILs) and in SE (64.8% of the ILs) in 2011–2019 compared to 2001–2010 signals a worrying rise in vulnerability recently. We advise the adoption of policies by the State, such as combating illegal activities, and strengthening National Policy for Environmental and Territorial Management of ILs. Herein, our vulnerability quantification can prioritize help to certain ILs, and the understanding of the contribution of the underlying dimensions can direct these policies, possibly according to the vulnerability profile of each IL.

1. Introduction

In recent decades, the vulnerability of integrated human-environment systems has become a prominent theme in the fields of science related to sustainability and global environmental and climate change (Turner et al., 2003a; Füssel, 2007; Hinkel, 2011; Nelson et al., 2010; Nguyen et al., 2016; Dumenu and Obeng, 2016; Lapola et al., 2020; Umamaheswari et al., 2021). Diverse research areas in natural and social science have used vulnerability approaches in different contexts, resulting in a wide range of vulnerability definitions and methods (Adger, 2006; Turner et al., 2003a; Gallopín, 2006; Nguyen et al., 2016; Dumenu and Obeng, 2016; Jurgilevich et al., 2017; Berrouet et al., 2019; Nguyen and Leisz, 2021). Despite the challenges that exist in estimating the vulnerability of human and environmental systems, because it is not an observable phenomenon, vulnerability assessments have the potential to identify vulnerable regions or population groups, provide information to monitoring strategies, and have an important role in guiding the formulation of adaptation plans to climate and environmental change (Nguyen et al., 2016).

The theoretical framework on vulnerability to climate change from the Intergovernmental Panel on Climate Change (IPCC) (McCarthy et al., 2001; Schneider et al., 2007) provides a starting point to guide the development of vulnerability assessments. In the IPCC Third and Fourth Assessment Reports, vulnerability was defined as the degree to which a system is susceptible to suffer damage or the lack of capacity to cope with adverse effects when exposed to change. In this conception, vulnerability is understood as a function of the sensitivity and adaptive capacity of systems (which can be human, environmental, or

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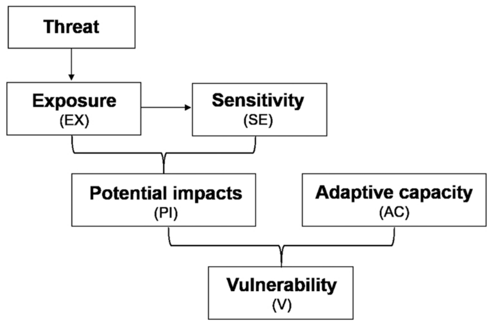

Fig. 1. IPCC's conceptual vulnerability framework (McCarthy et al., 2001; Schneider et al., 2007).
Adapted from Nguyen et al. (2016).

human-environment systems) when they are exposed to threats or changes.

Adopting the IPCC vulnerability framework (McCarthy et al., 2001; Schneider et al., 2007), a growing number of vulnerability assessments has been developed for a wide range of scales, from local to global extent, and approaching different social and environmental contexts. Such studies arise to estimate the vulnerability of populations living in extreme poverty (Leichenko and Silva, 2014); the vulnerability of ecosystem services (Metzger et al., 2006); the rural livelihood vulnerability (Eakin and Bojórquez-Tapia, 2008); the vulnerable situation of populations in the face of environmental and climate change (Cutter et al., 2003; o'Brien et al., 2004; Pandey et al., 2017; Bankoff et al., 2004; Nguyen and Leisz, 2021; Umamaheswari et al., 2021); as well as the vulnerability of economic sectors (Allison et al., 2009) and agricultural production (Ahumada-Cervantes et al., 2017) to climate change.

The Indigenous Lands (ILs) in the Brazilian Amazon are home to the largest population of Indigenous peoples in the world and are currently a worrying case of human-environment (Liu et al., 2007) systems facing a multitude of environmental threats (Rorato et al., 2021). The ILs in the Brazilian Amazon (hereafter, referred to as Amazonian ILs) cover over 1160,000 km^2, representing 22% of this region (National Indian Foundation – FUNAI, 2019b; Socioenvironmental Institute - ISA, 2019b), and constitute the traditional territory of about 355 thousand Indigenous people and its rich cultural diversity (Socioenvironmental Institute - ISA, 2019b; Begotti and Peres, 2020). At the same time, Amazonian ILs are crucial for an effective global strategy to preserve tropical forests, with the potential to contribute to climate change mitigation and biodiversity conservation (Walker et al., 2014; Garnett et al., 2018; Baragwanath and Bayi, 2020; Álvaro Fernández-Llamazares, 2020).

Historically, Amazonian ILs have faced internal and external pressure from multiple environmental threats with varying severity (Carneiro Filho and Souza, 2009; Begotti and Peres, 2019; Red Amazónica de Información Socioambiental Georreferenciada – Raisg, 2020; Indigenist Missionary Council – CIMI, 2020; Ferrante and Fearnside, 2019; Rorato et al., 2020, 2021). Herein, environmental threats are the degrading processes or activities that contribute to environmental degradation and reduce the environmental integrity of ILs, as defined by Rorato et al. (2021). Among the most important environmental threats affecting ILs are those related to forest cover reduction, such as deforestation, forest degradation, and fire, as well as the facility of access provided by roads, and the economic activities such as logging, mining, agriculture, and livestock farming (Carneiro Filho and Souza, 2009; Red Amazónica de Información Socioambiental Georreferenciada - Raisg, 2020; Indigenist Missionary Council – CIMI, 2019, 2020; Ferrante and Fearnside, 2020; Ferrante et al., 2021; Rorato et al., 2020, 2021).

While Amazonian ILs have shown to be important barriers to deforestation in the past, keeping the forest intact even in places with high deforestation pressure (Nolte et al., 2013), they have faced substantial increases in fire and deforestation rates in recent years (National Institute for Space Research – INPE, 2020a, 2020b). According to INPE's Amazon Deforestation Monitoring Program (PRODES), 497.4 km^2 was deforested within the Amazonian ILs in 2019 compared to 260.6 km^2 in 2018, an increase of 90.9%. In the same period, the invasions for land speculation and illegal exploitation of natural resources have increased too (Indigenist Missionary Council – CIMI, 2019, 2020). Amazonian ILs have been encroached by illegal loggers, farmers, squatters, and gold miners, directly and indirectly (e.g. through environmental degradation) increasing the vulnerability of Indigenous peoples (Indigenist Missionary Council – CIMI, 2019, 2020; Begotti and Peres, 2019).

To date, two studies have performed a risk (Walker et al., 2014) or the vulnerability (Lapola et al., 2020) assessment on Amazonian Indigenous Lands combined with other categories of protected areas (PAs). Walker et al. (2014) assessed the risk situation of carbon stocks in different categories of PAs and ILs in the Amazon Basin. They mapped the distribution of current and potential risk factors (i.e., agriculture, grazing, mining, petroleum, timber, and transportation) in these areas and surroundings. However, the study neither quantified the importance of each risk factor, nor estimated the PAs' and ILs' degree of vulnerability. In contrast, Lapola et al. (2020) developed a vulnerability assessment, combining climatic-change hazard indicators with indicators of resilience (IL/PA size, native vegetation cover, and the probability of climate-driven vegetation transition) to investigate the vulnerability of PAs and ILs in Brazil to climate change. According to their results, 80% of the areas of high or moderate vulnerability to changes induced by climate change are ILs.

Despite the important contributions of these studies, there is a gap in the knowledge of the current vulnerability of Amazonian ILs to environmental threats unrelated to climate change. Given the worsening threats over Amazonian ILs described above, Brazil requires scientific studies of Indigenous territories' environmental vulnerability to support the current and future application of public policy strategies. In addition, the identification of vulnerable ILs in the Amazon is crucial for a better allocation of conservation measures, for compliance with international human rights commitments, and so allows directing adequate safeguards to protect them.

This study aims to contribute to filling this knowledge gap by providing the first assessment of the environmental vulnerability of Amazonian ILs. We intend to answer the following research questions: *i) What is the environmental vulnerability of ILs in the Amazon? and ii) How have the exposure and sensitivity of Amazonian ILs to environmental threats changed in the past ten years?* Hereto, we adopted the vulnerability theoretical framework of IPCC (McCarthy et al., 2001; Schneider et al., 2007) in an indicator-based approach to describe the exposure and sensitivity to the main threats and the adaptive capacity of Indigenous peoples to deal with these threats. The exposure and sensitivity indicators were quantified using spatial data of deforestation, forest degradation, land-use, fire, roads, and mining, inside and around the ILs. Indicator values are assessed for two periods, 2001–2010 and 2011–2019, to assess temporal changes in exposure and sensitivity patterns, as well as overall (2001–2019). Adaptive capacity was estimated through indicators that represent Indigenous self-organization, level of education, access to knowledge, land ownership, external incomes, and institutional arrangement.

2. Methods

2.1. Theoretical framework and scope

Conceptually, the vulnerability of a system depends on the nature of the threat to which the system in question is exposed and the system's sensitivity that will make it more vulnerable to certain types of threats than to others (Gallopín, 2006). In the IPCC Third and Fourth Assessment Reports (McCarthy et al., 2001; Schneider et al., 2007), the vulnerability of a system is described to be a function of three

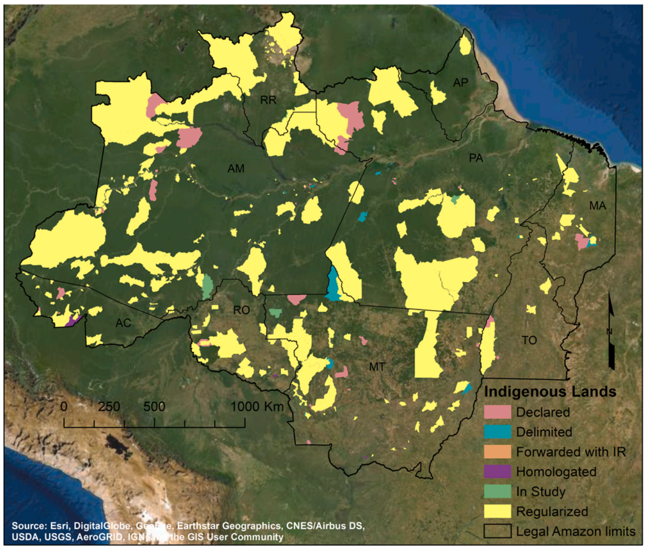

Fig. 2. Indigenous Lands in the Legal Amazon region. Colors indicate the legal status of recognition process. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.) Data source: FUNAI (2019a).

overlapping components (Fig. 1): 1) exposure (EX), 2) sensitivity (SE), and 3) adaptive capacity (AC). In summary, exposure defines the nature and amount to which the system is exposed to threats; sensitivity reflects the system's potential to be affected by changes because of these threats; and adaptive capacity characterizes the system's ability to respond to these effects (Turner et al., 2003b; Metzger et al., 2006; Gallopín, 2006; Polsky et al., 2007). Following this conceptual approach, potential impacts on the system are defined as a function of exposure and sensitivity. In its turn, the system's vulnerability is a function of potential impacts and its adaptive capacity (Metzger et al., 2006; Nguyen et al., 2016) (Fig. 1). Thus, a system is expected to be more vulnerable if it is exposed to threats, if it is sensitive to those threats and their consequent impacts, and if it has a low adaptive capacity to cope with those impacts (McCarthy et al., 2001; Schneider et al., 2007).

The challenge of vulnerability assessments is making the theoretical framework operational (Tate, 2013). The selection of what should be included depends on the system at risk, the context (o'Brien et al., 2007), and the intention of the assessment. One of three approaches is generally used in vulnerability assessments: a participatory, a simulation-model-based, or an indicator-based approach (Nguyen et al., 2016). The latter approach, the one applied in this study, is used most often. It considers a set of indicators to explain the three vulnerability components - EX, SE, and AC (Luers et al., 2003; Luers, 2005; Gallopín, 2006; Schröter et al., 2005). Indicators are variables that represent attributes, such as characteristics of the system relevant for its condition (Hinkel, 2011). Usually, after selecting indicators, they are scaled, weighted, and combined to form a final index for each vulnerability component, which can then be aggregated in a final system's vulnerability index (Schröter et al., 2005; Reckien, 2018).

In this study, we adopted the theoretical vulnerability framework by IPCC (McCarthy et al., 2001; Schneider et al., 2007) and followed the steps described by Schröter et al. (2005) to make this concept operational and to assesses the environmental vulnerability of Amazonian ILs: (1) To hypothesize who is vulnerable to what; (2) To find indicators for the elements that comprise the vulnerability, i.e., to develop a place-based set of indicators relating to EX, SE and AC of the system; and (3) To weight the indicators of EX, SE, and AC to produce measures of the contribution of each component to the system's vulnerability. The three-step operationalization is described in the following subsections, after the description of the study area.

2.2. Study Area

The Brazilian Legal Amazon (BLA) is a political-administrative region covering approximately 5 million km^2, corresponding to approximately 58.9% of the Brazil's territory. The BLA comprises the states of Acre (AC), Amapá (AP), Amazonas (AM), Pará (PA), Rondônia (RO), Roraima (RR), Mato Grosso (MT), Tocantins (TO), and part of Maranhão (MA) (Brazilian Executive Power, 1966). This region encompasses rainforest formations and associated ecosystems. Under Brazil's current Federal Constitution and international Indigenous rights treaties that Brazil is a party of, Indigenous peoples have the original right to exclusive usufruct of the lands they traditionally occupy (National Indian Foundation – FUNAI, 2019a; International Labour Organization - ILO, 1989; Assembly, 2007). Hereto, we considered the ILs located entirely within the BLA region for all legal phases of land regularization derived from the FUNAI (National Indian Foundation) website (National Indian Foundation – FUNAI, 2019a) (Fig. 2). In Brazil, the process of regularizing Indigenous lands comprises different stages and usually takes years to complete. Currently, of the 383 ILs in the Legal Amazon, 325 ILs are Regularized, while the others are in one of the following phases of regularization, listed since the initial phase: In Study (6), Delimited (11), Declared (31), Forwarded with Indigenous Reserve (7), and Homologated (3) (National Indian Foundation – FUNAI, 2019a). The explanation of each phase of the process of land regularization of ILs by the State is presented in Table A.1.

2.3. Hypothesizing who is vulnerable to what

In this study, we focus on the environmental vulnerability of Amazonian ILs and the environmental threats that make them vulnerable. We suppose the environmental vulnerability emerges because of the existence of a set of threats inside and surrounding the ILs, affecting the ILs' environmental integrity and the Indigenous peoples' safety and livelihood (Carneiro Filho and Souza, 2009; Ricardo and Ricardo, 2011; Indigenist Missionary Council – CIMI, 2019; Rorato et al., 2021). In this sense, we defined our system of interest as an integrated human-environment system, as people interact with the natural component (Liu et al., 2007). This system is comprised of the IL and its surroundings (natural component) and the resident Indigenous population(s) (human component). Other research has demonstrated that numerous one-directional interactions and feedback loops between these components exist (Turner and Robbins, 2008; Iwamura et al., 2014; Levis et al., 2017). Interactions present in the Amazonian ILs are further elaborated below.

According to the literature and several reports consulted, the main threats associated with the environmental vulnerability of Amazonian ILs are deforestation, forest degradation, fire, advancement of the agricultural frontier, mining, and IL access provided by roads (Nepstad et al., 2006,Nepstad et al., 2008; Carneiro Filho and Souza, 2009; Ricardo and Ricardo, 2011; Le Tourneau, 2015; Socioenvironmental Institute - ISA, 2019a; Red Amazónica de Información Socioambiental Georreferenciada – Raisg, 2020; Ferrante et al., 2021; Rorato et al., 2021). This set of environmental threats was grouped into three dimensions: forest cover, economic activity, and access. As our objective is to assess the different historical threats suffered by Indigenous Lands in the past until the year 2019, the inclusion of indicators related to future vulnerabilities, such as climate change, is beyond the scope of this study.

The first dimension, forest cover, is related to the threats causing direct disturbances of the forest cover and consequential negative impacts. Deforestation, i.e., the forest's clear-cutting, causes loss of habitat and biodiversity, soil erosion, silting and drought of rivers. Forest degradation, i.e. the gradual long-term process of forest cover loss mainly because of selective logging and fire (Diniz et al., 2015; INPE, 2008), results in changes in the forest's structure and its associated ecological processes and makes the forest drier and more susceptible to fire (Barlow et al., 2020). Lastly, the spreading of uncontrolled fire causes the loss of forest cover and biodiversity, besides aggravating respiratory diseases,

Table 1
Vulnerability components, its dimensions, indicators, weights, and data source.

Component	Dimension	Indicator	Quantification	Weight	Period	Source
EX	Forest Cover	Deforestation	accumulated deforested area in BF (%)	0.166	2001–2019, 2001–2010, 2011–2019	Prodes (INPE)
	Forest Cover	Forest degradation	accumulated degraded forest area in BF (%)	0.154	2001–2019, 2001–2010, 2011–2019	Degrad/Deter (INPE)
	Forest Cover	Fire	accumulated burned area in BF (%)	0.098	2001–2019, 2001–2010, 2011–2019	Burned Area Product (MODIS)
	Economic activity	Agriculture	cropland area in BF (%)	0.118	2010 and 2018	(Câmara et al., 2020)
	Economic activity	Livestock	pasture area in BF (%)	0.156	2010 and 2018	(Câmara et al., 2020)
	Economic activity	Mining	nº of mining occurrences in BF	0.171	2018	RAISG
	Access	Roads	road density in BF (km/km^2)	0.137	2010 and 2017	LAPIG and RAISG
SE	Forest Cover	Deforestation	accumulated deforested area in IL (%)	0.166	2001–2019, 2001–2010, 2011–2019	Prodes (INPE)
	Forest Cover	Forest degradation	accumulated degraded forest area in IL (%)	0.154	2001–2019, 2001–2010, 2011–2019	Degrad/Deter (INPE)
	Forest Cover	Fire	accumulated burned area in IL (%)	0.098	2001–2019, 2001–2010, 2011–2019	Burned Area Product (MODIS)
	Economic activity	Agriculture	cropland area in IL (%)	0.118	2010 and 2018	(Câmara et al., 2020)
	Economic activity	Livestock	pasture area in IL (%)	0.156	2010 and 2018	(Câmara et al., 2020)
	Economic activity	Mining	nº of illegal mining occurrences in IL	0.171	2018	RAISG
	Access	Roads	road density in IL (km/km^2)	0.137	2010 and 2017	LAPIG and RAISG
AC	Natural Resources	Forest cover integrity	largest forest patch index IL+BF (%)	0.101	2018	(Câmara et al., 2020)
	Human Resources	Education level	literated Indigenous people over 10 years (%)	0.087	2010	Census IBGE
	Human Resources	Access to knowledge	nº of thematic projects	0.154	1988–2019	SisArp (ISA)
	Human Resources	Self-organization	nº of Indigenous organizations	0.199	1988–2019	SisArp (ISA)
	Human Resources	Institutional arrangement	nº of partner and funding organizations	0.123	1988–2019	SisArp (ISA)
	Economic Resources	External incomes	total funds raised for projects (R$)	0.149	1988–2019	SisArp (ISA)
	Law Resources	Land ownership	status of IL regularization	0.188	2019	FUNAI

unbalancing the local ecosystem (Cochrane and Schulze, 1999; Nepstad et al., 2008; Aragão et al., 2018; de Oliveira et al., 2020), destroying subsistence crops, and leading to the loss of Indigenous villages (Lacerda, 2013). The combination of these threats over the ILs' forest can impact Indigenous peoples by reducing natural resources for subsistence, such as hunting, fish, fruits, trees used for construction, and medicinal herbs. Also, illegal logging is responsible for many violent conflicts involving Indigenous people and the invaders (Ricardo and Ricardo, 2011; Indigenist Missionary Council - CIMI, 2020a).

The economic-activity dimension is expressed by agriculture, livestock, and mining. Currently, several ILs are occupied by illegal squatters who carry out agricultural activities. Besides, the surrounding areas of some ILs are dominated by croplands or pastures. In the Amazon, the expansion of livestock and croplands represents a key driver of environmental degradation (Gibbs, 2010; Camara et al., 2015), with negative impacts on water availability, soil quality, biodiversity, and local climate (Gibbs, 2010; Lambin and Meyfroidt, 2011; Turner et al., 2007). The advancement of agricultural activities threatens the environmental integrity of ILs by driving deforestation, increasing the forest's exposure to fire, and contaminating soil and water with pesticides (Begotti and Peres, 2020; Indigenist Missionary Council - CIMI, 2020a). Furthermore, the presence of squatters and farmers in these territories has resulted in many situations of conflict and violence against Indigenous peoples (Ricardo and Ricardo, 2011; Indigenist Missionary Council – CIMI, 2019, 2020).

Mining is widely known for its serious social and environmental impacts, such as deforestation, contamination of soil and water bodies by toxic waste, depletion of local biodiversity and ecosystem services, human contamination and local economic collapse (Sonter et al., 2017; Horowitz et al., 2018; Vega et al., 2018; Siqueira-Gay et al., 2020; Siqueira-Gay and Sánchez, 2021; Diele-Viegas et al., 2020). In addition, like the other economic activities described above, mining is also responsible for several situations of conflict and violence against Indigenous peoples (Horowitz et al., 2018; Indigenist Missionary Council - CIMI, 2020a). Currently, several Amazonian ILs are invaded by illegal gold miners (Rorato et al., 2020; Siqueira-Gay and Sánchez, 2021).

Finally, the third dimension, access, is expressed by the facility of access provided by roads. Historically, in the Amazon region, the opening of roads is directly linked with the process of clearing forest, typically to establish new areas of settlement and land acquisition (Alves, 2002; Ferrante et al., 2021, 2020; Ferrante and Fearnside, 2020). In general, deforestation, forest degradation, and fire are most intense in areas of a consolidated and expanding agricultural frontier (Aguiar et al., 2007; RAISG, 2015) and associated with road networks (Alves, 2002; Soares-Filho et al., 2006; Aguiar et al., 2007). The set of threats described here was the basis for the development of the EX and SE indicators in our vulnerability assessment (see next section).

2.4. Indicators of the exposure, sensitivity, and adaptive capacity components

Indicators are selected as proxy variables to explain theoretical components of the system's vulnerability (Tate, 2013). The EX indicators were computed for a buffer zone (BF) of 10 Km around each IL (outside the IL), excluding the IL itself, while the SE indicators were computed from within the boundaries of each IL (inside the IL), in line with Rorato et al. (2021). The buffer delimitation range was based on previous studies (Nepstad et al., 2006; Soares-Filho, 2010; Cabral et al., 2018) and on environmental regulations, which establish a 10 km-radius surrounding protected areas to preserve its ecosystems of all activities that may cause negative damages.[1] The indicators for the

[1] The repealed CONAMA (National Environmental Council) Environmental Resolution no. 13/1990, Decree 99.274/1990, 208 and Interministerial Ordinance No. 60 of 2015, in case of mining exploitation and construction of railways.

AC component were compiled per IL, based on the demographics and conditions of the peoples living within them. This is often a single ethnic group per IL, but sometimes multiple ones.

The vulnerability components' definition and their respective indicators are detailed in the next sections and summarized in Table 1. The EX and SE indicators were calculated for our full period of analysis, 2001–2019, as well as for two separate periods to answer research question ii, 2001–2010 (*t1*) and 2011–2019 (*t2*). For the AC component, the lack of census data (required to compute the AC indicators) for different years did not allow a temporal comparison for that component.

According to the IPCC vulnerability framework, it is important to assess all relevant components/ dimensions of the system under study, even if they present some correlation. Thus, in this work, we neither assume the absence of correlation between the indicators, nor correct for correlated indicators, in line with Crozier et al. (2019) and Bueno-Pardo et al. (2021). For transparency about the correlations, a correlogram with all the indicators is presented in the Appendix (A.4).

2.4.1. Exposure (EX)

The first component of vulnerability, the exposure, is defined as the nature and degree to which systems are exposed to threats (McCarthy et al., 2001; Schneider et al., 2007). More specifically, it is described as the magnitude, duration, and/or extent to which the system is in contact with, or subject to, the threat (Luers, 2005; Adger, 2006). In this component, the indicators were created from the following external threats calculated in the ILs' BF: deforestation, forest degradation, fire, livestock, agriculture, road access, and mining.

The indicator of ILs' exposure to deforestation was calculated as the accumulated percentage of deforested areas relative to the BF area for each period, based on data from INPE's Amazon Deforestation Monitoring Program (PRODES) (National Institute for Space Research – INPE, 2020a).

The ILs' exposure to forest degradation was calculated by the accumulated percentage of the area of degraded forest relative to the BF area for each period, based on data from DEGRAD (2007–2016) and DETER (2016–2019) (INPE, 2008). We adopt the definition of forest degradation used by INPE: the process of the gradual loss of forest cover due to the effect of logging and forest fire, of at least 6.25 ha, which does not qualify as clear cut deforestation by PRODES. Overlapping areas, having suffered forest degradation more than once, have been discounted. As there are no forest degradation data prior to 2007, our estimate degradation in *t1* may be an underestimation. However, as there is a lot of recurrence of degraded areas, this underestimation is partially compensated (INPE, 2008; Rodrigues et al., 2019).

The indicator of ILs' exposure to fire was calculated as the accumulated percentage of burned area relative to the BF area for each period, using data from MODIS' (NASA's Moderate Resolution Imaging Spectroradiometer) Global Burned Area Product (Collection 6) (Giglio et al., 2018). This product results from the daily detection of burned areas at a spatial resolution of 500 m. Overlapping areas, burned more than once, have been discounted.

The indicators of ILs' exposure to agriculture and livestock were estimated by the percentage of pastures and cropland areas relative to the BF area at the end of each period (2010 and 2019). Hereto, we used the annual maps of land-use and land-cover (LULC) of the Brazilian Amazon developed from MODIS time series by Câmara et al. (2020).

The indicator of exposure of ILs to road access was expressed by the density of roads in the BF by 2010 and 2017. The road density was calculated by dividing the sum of the lengths of the roads in the BF by the area of the BF (km/km^2). The 2010 road network data was obtained from the LAPIG's map platform (Laboratory of Image Processing and Geoprocessing at the Federal University of Goiás) and derived from several institutional sources, such as the IBGE (Brazilian Institute of Geography and Statistics), DNIT (National Infrastructure and Transport Department), and ANTT (National Land Transportation Agency) (Laboratory of Image Processing and Geoprocessing at the Federal University of Goiás – LAPIG, 2019). The 2017 road network data was obtained from the RAISG (Amazon Network of Georeferenced Social and Environmental Information) (Rede Amazônica de Informação Socioambiental Georreferenciada – RAISG, 2019) derived from IBGE data.

Lastly, the indicator of the exposure of ILs to mining was expressed as the number of occurrences of mining activities in the BF by 2018. The data used in this indicator were compiled by RAISG (Rede Amazônica de Informação Socioambiental Georreferenciada – RAISG, 2019). No earlier data were available for this indicator.

2.4.2. Sensitivity (SE)

The second vulnerability component, sensitivity, is described as the degree to which a system is affected, either adversely or beneficially, by stimuli (McCarthy et al., 2001; Schneider et al., 2007). In this conception, the sensitivity can be measured in terms of the quantity of transformation experienced by the system (Luers, 2005; Gallopín, 2006). Since some characteristics of the system determine its sensitivity to the set of exposures (Turner et al., 2003a), we considered sensitivity indicators correspondent to each exposure threat in our vulnerability assessment. To make the sensitivity of ILs operational, we estimated the environmental threats inside the ILs (Table 1) to measure the degree to which the system (the IL) is affected. The seven sensitivity indicators (deforestation, forest degradation, fire, livestock, crops, roads, and mining) are calculated in exactly the same way as the exposure indicators, however, they are computed within the IL rather than the BF zones.

Regarding the indicators of ILs' sensitivity to agriculture and livestock, in this study, we are interested in detecting predominant areas of agricultural practices on a large-scale. We could not distinguish between external/invasive agriculture practices and internal/Indigenous managed agriculture practices based on the data used. However, the development of these practices, large-scale agriculture and livestock, by Indigenous populations is unusual; when large-scale agriculture and livestock occur within Indigenous Lands, they are often developed by non-indigenous invaders and can be thus considered an environmental threat. So far we know only one exception, the case of IL Utiariti (MT), where a small group of Indigenous people from the Paresis ethnicity practice large-scale agriculture, producing grains such as soy, corn and beans with the support of non-indigenous farmers in the region. However, this activity is not legitimated by the rest of the resident Indigenous population and is not allowed by law.

2.4.3. Adaptive capacity (AC)

The third component, adaptive capacity, is defined as the ability of the system to adjust to changes or threats to moderate potential damages, take advantage of opportunities, or cope with the consequences (Metzger et al., 2006; Gallopín, 2006; McCarthy et al., 2001; Schneider et al., 2007). The AC can be understood as the extent to which a system can react and change its circumstances to move to a less vulnerable condition, and it depends on the quantity and quality of resources that the system has (Turner et al., 2003a; Luers, 2005). As such, the AC represents Indigenous peoples' capacity to deal with environmental degradation and illegal occupation of their lands. The AC component was designed to capture the human component of the integrated human-environment system and it is interrelated with the environmental dimension captured by the EX and SE components.

Since the adaptive capacity depends on the quantity and quality of the system's resources, we divided this component into four dimensions based on literature: 1) natural resources, 2) human resources, 3) law resources, and 4) economic resources (Moss et al., 2001; o'Brien et al., 2004; Metzger et al., 2006; Pandey et al., 2017). For each dimension, we selected one or more indicators (Table 1) as explained below.

First, the natural resources dimension refers to the level of environmental integrity of ILs, represented by a landscape metric of vegetation cover integrity, the Largest Patch Index (LPI), computed over the total landscape area (IL + BF). Input data for this metric are the annual

LULC maps described above (Câmara et al., 2020). The higher the LPI, the higher the integrity of the original ILs' vegetation area and the lower the fragmentation (McGarigal, 2015). Fragmented landscapes tend to be more susceptible to fire, to present reduced provision of ecosystem services, and lower quality of habitat for various species; reducing the availability of food (hunting, fruits, vegetables) (Broadbent et al., 2008; Laurance et al., 2011). Thus, the more fragmented the vegetation within and around the IL, the lower the quality of life and the availability of resources for the Indigenous population (de Araujo Lima Constantino, 2016) and, consequently, the lower their capacity to face potential impacts on their territories.

The second dimension, human resources, aims to capture Indigenous peoples' access to formal education, knowledge, and information in various contexts, as well as the autonomy of Indigenous peoples to self-organize and establish partnerships with different spheres of the majority society. For this dimension, we use four indicators. First, as an indicator of the level of formal education, we considered the percentage of literate Indigenous people of at least ten years old in each IL in 2010. Data were obtained from the IBGE Demographic Census (Brazilian Institute of Geography and Statistics – IBGE, 2010).

Second, as an indicator of self-organization, we computed the number of Indigenous organizations involved in developing projects per IL. Our reasoning is based on the fact that the history of empowerment of Indigenous peoples in Brazil is closely linked to the creation of Indigenous organizations for self-representation. It is from these Indigenous organizations that various Indigenous groups have been fighting for their rights and articulating their demands for territory, health, and education, from the 1980 s to the present day. These organizations relate to different spheres of the majority society, such as government sectors, non-governmental organizations, and private organizations. It is through these Indigenous organizations that partnerships, projects, and programs are established for these peoples. Third, as an indicator of Indigenous peoples' access to knowledge and information in different contexts, we considered the number of thematic projects developed in each IL. Finally, as an indicator of the institutional arrangement, we counted the number of unique institutions and organizations that executed, financed, proposed, and acted as partners in the development of projects per IL in the period considered. For these last three indicators, data from the *Instituto Socioambiental* (ISA) database of the Protected Areas Information System (SisArp) were collected on August 7, 2019. Altogether, around 2200 projects were developed or started between 1988 and 2019, and are considered in this study. The thematic projects were developed for different purposes, such as training, social mobilization, encouraging culture, environmental and territorial sustainable practices, health, school education, citizenship, and political representation.

The third dimension, economic resources, refers to the financial capacity of Indigenous peoples derived from external incomes. Here, we used the total amount of funds raised for projects development per IL during 1988–2019. With this indicator we assume that the availability of external partners is a factor that influences the adaptive capacity of Indigenous peoples. This indicator also was obtained from the SisArp data set from ISA and was computed in Brazilian Real.

The final dimension, law resources, considers the legal status of ILs as an indicator. We believe that the land regularization of ILs by the State increases the adaptive capacity of Indigenous peoples by descreasing environmental degradation and illegal occupation in Amazonian ILs. To support this claim, we compared Regularized ILs between 1997 and 2018 in an exploratory analysis. We found a significant difference between the yearly rates of deforestation before and after the regularization (Wilcoxon test: $V = 880$, $p < 0.00001$), where the deforestation rate before the regularization was larger than afterwards. This trend also was verified in other studies (Socioenvironmental Institute - ISA, 2019a; Baragwanath and Bayi, 2020). In our indicator, the legal status of ILs was classified between 0 and 1 according to the sequence of steps followed until the conclusion of the IL recognition process. The values assigned to ILs status were: In Study = 0.2, Delimited = 0.4, Declared and Forwarded IR = 0.6, Homologated = 0.8 and Regularized = 1.0.

2.5. Vulnerability Index

All indicators calculated as percentages were converted to fractions ranging between 0 and 1. To make the set of indicators comparable, the other indicators were scaled between 0 and 1 using the Minimum-Maximum method, as generally done to overcome the incompatibilities to combine different measurement units (Tate, 2013; Nguyen et al., 2016).

Given that the indicators represent different characteristics that constitute the vulnerability of the system under analysis, we do not consider the influence of the indicators equal. Weighting was applied to express the relative importance of each indicators to their respective component. Different methods to determine the weight values in the multi-criteria analysis are found in literature, such as based on expert opinions or the involvement of stakeholders (Tate, 2013; Nguyen et al., 2016).

Here, we used the knowledge of ten experts on Indigenous issues in the Amazon to establish the indicators' weights of the three vulnerability components. The experts were asked to classify the indicators according to the degree of environmental threat they represent to ILs (EX and SE components); and to classify the indicators according to their importance for the capacity of Indigenous peoples to deal with environmental threats in their territories (AC component). The rankings were averaged over the ten experts and linearly converted to weights, see Weight column in Table 1. According to the experts' perception, the order of importance of the indicators related to the EX and SE of the Amazonian ILs was (from the most important to the least important): mining, deforestation, livestock, forest degradation, road access, agriculture, and fire. The order of importance of the AC indicators was (from the most important to the least important): self-organization, land ownership, access to knowledge, external incomes, institutional arrangement, forest cover integrity, and education level.

Using the Weighted Linear Combination (Voogd, 1983) and an additive approach (Reckien, 2018), the indicators were combined into a final value to each vulnerability component (EX, SE, and AC) per IL, according to Eqs. (1)–(3). The additive approach consists of the sum of indicators that are supposed to contribute to the vulnerability of a given system (Reckien, 2018).

$$EX = \sum_{i=m}^{n} (Vex_i * Wex_i) \tag{1}$$

$$SE = \sum_{i=m}^{n} (Vse_i * Wse_i) \tag{2}$$

$$AC = \sum_{i=m}^{n} (Vac_i * Wac_i) \tag{3}$$

where:

Vex_i = the calculated value for the EX indicator i
Wex_i = the assigned weight by experts for the EX indicator i
Vse_i = the calculated value for the SE indicator i
Wse_i = the assigned weight by experts for the SE indicator i
Vac_i = the calculated value for the AC indicator i
Wac_i = the assigned weight by experts for the AC indicator i

Finally, the three vulnerability components were combined in a final vulnerability index per IL. Since vulnerability is the interrelation of the exposure and the sensitivity of the system to multiple threats, with the adaptive capacity as the potential of the system to decrease their impact, vulnerability is expressed as in Eqs. (4) and (5) (Metzger et al., 2006; Taubenböck et al., 2008).

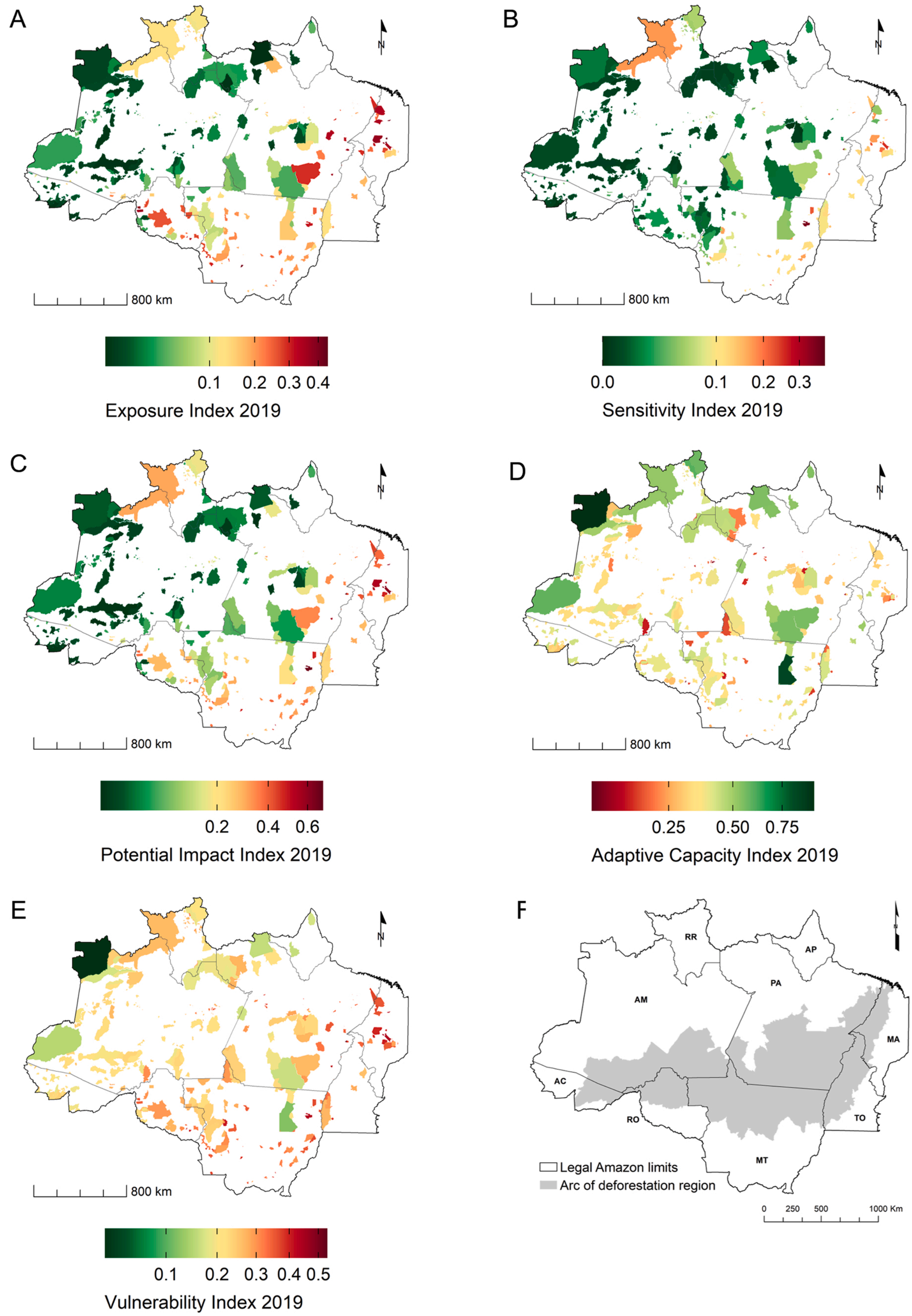

Fig. 3. Final indexes of exposure (A), sensitivity (B), potential impact (C), adaptive capacity (D), and vulnerability (E) by 2019 of the Amazonian Indigenous Lands. Limits of the regions of the Legal Amazon and the Arc of Deforestation (F). The variables (colors) are displayed on a quadratic scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Final values of exposure, sensitivity, potential impact, adaptive capacity, and vulnerability indexes of Indigenous Lands in the Amazon.

	Exposure		Sensitivity		Potential impact		Adaptive capacity		Vulnerability	
Rank	IL name	Value	IL name	Value	IL name	Value	IL name	Value	IL name	Value
1	Lagoa Comprida	0.435	Praia do Indio	0.381	Tuwa Apekuokawera	0.688	Tanaru	0.064	Tuwa Apekuokawera	0.532
2	Geralda Toco Preto	0.430	Maraiwatsede	0.352	Maraiwatsede	0.665	Cobra Grande	0.078	Praia do Indio	0.478
3	Rio Pindare	0.418	Tuwa Apekuokawera	0.343	Lagoa Comprida	0.633	Jauary	0.084	Lagoa Comprida	0.455
4	Umutina	0.410	Apipica	0.269	Praia do Indio	0.630	Tuwa Apekuokawera	0.092	Urucu/Jurua	0.454
5	Urucu/Jurua	0.380	Tadarimana	0.258	Urucu/Jurua	0.619	Praia do Mangue	0.116	Rio Pindare	0.443
6	Igarape Ribeirao	0.379	Cana Brava/Guajajara	0.251	Rio Pindare	0.610	Vista Alegre	0.123	Maracaxi	0.441
7	Sororo	0.371	Jarudore	0.246	Cana Brava/Guajajara	0.603	Maracaxi	0.134	Cana Brava/Guajajara	0.435
8	Arariboia	0.369	Recreio/Sao Felix	0.246	Las Casas	0.575	Estacao Parecis	0.135	Maraiwatsede	0.431
9	Las Casas	0.369	Urucu/Jurua	0.239	Jarudore	0.560	Jacareuba/Katauixi	0.136	Tanaru	0.429
10	Igarape Lage	0.362	Governador	0.221	Governador	0.543	Igarape Taboca do Alto Tarauaca	0.136	Las Casas	0.427
11	Cana Brava/Guajajara	0.351	Urubu Branco	0.221	Arariboia	0.541	Ituna/Itata	0.138	Jarudore	0.422
12	Morro Branco	0.347	Las Casas	0.206	Geralda Toco Preto	0.529	Menku	0.139	Praia do Mangue	0.420
13	Tuwa Apekuokawera	0.345	Bacurizinho	0.204	Bacurizinho	0.501	Murutinga/Tracaja	0.139	Pequizal	0.412
14	Rio Omerê	0.345	Rodeador	0.203	Umutina	0.491	Paukalirajausu	0.142	Geralda Toco Preto	0.412
15	Pequizal	0.344	Lagoa Comprida	0.199	Tadarimana	0.481	Pirititi	0.148	Menkü	0.409

For the EX, SE, PI, and V indexes, the 15 ILs with the highest values are presented. For the AC index, the 15 ILs with the lowest values are presented.

$$PI = EX + SE \tag{4}$$

where:

PI = *potential impact index*
EX = *exposure index*
SE = *sensitivity index*

$$V = \frac{PI + (1 - AC)}{3} \tag{5}$$

where:

V = *vulnerability index*
PI = *potential impact index*
AC = *adaptive capacity index*

Using these Equations to combine the values of vulnerability components, we quantified the vulnerability of all Amazonian ILs by 2019 and assess changes over time in exposure and sensitivity between *t1* (2001–2010) and *t2* (2011–2019). Due to the lack of data for mining in the period *t1*, the temporal comparison was made without considering the mining indicator for both components of EX and SE.

2.6. Sensitivity analysis

Sensitivity analysis has been widely recommended to understand the impact of uncertainties in the weights in weight-based approaches on the results of the analysis (Tate, 2013; Chen et al., 2010; Xu and Zhang, 2013). Since the assignment of the indicators' weights occurred through the experts' perception, and thus uncertain, we assess the relative influence of these weights on the vulnerability through a sensitivity analysis to get an impression of the robustness of our results (Chen et al., 2010; de Brito et al., 2019; Tate, 2013). We use the local One-At-a-Time (OAT) sensitivity analysis method, which analyzes the relative influence of one parameter at a time, keeping the other parameters fixed. This choice is justifiable, given that there are no interactions between indicators (Xu and Zhang, 2013) in our function.

In the OAT sensitivity analysis, the default weights of the indicators (Table 1) were multiplied by 0.5, 1 (default), 1.5 and 2, and the weight difference compared to the default value was redistributed over the other weights so that in each run the sum of the weights was 1 (Xu and Zhang, 2013). The effects of these weight changes on the median, minimum and maximum value of the vulnerability index over all ILs were assessed.

3. Results and discussion

3.1. Exposure, sensitivity, and potential impact 2001–2019

According to our results, the exposure index (EX) varied from 0.00018 to 0.44. The EX values of ILs in the 1st quantile (the least exposed ILs) varied from 0.00018 to 0.011. The EX values of ILs in the 4th quantile (the most exposed ILs) varied from 0.18 to 0.44. These most exposed ILs are concentrated in the region of the Arc of Deforestation and below (South of it), and in the North of Roraima state (Fig. 3A and 3F). The fifteen ILs more exposed in descending order are Lagoa Comprida, Geralda Toco Preto, Rio Pindaré, Umutina, Urucu/Juruá, Igarapé Ribeirão, Sororó, Arariboia, Las Casas, Igarapé Lage, Cana Brava/Guajajara, Morro Branco, Tuwa Apekuokawera, Rio Omerê, and Pequizal (Table 2).

The sensitivity index (SE) varied from 0 to 0.38. The SE values of ILs in the 1st quantile (the least sensitive ILs) varied from 0 to 0.0028. The SE values of ILs in the 4th quantile (the most sensitive ILs) varied from 0.087 to 0.38. Similar to the exposure, the most sensitive ILs are concentrated in the Arc of Deforestation region and below, and in the state of Roraima (Fig. 3B). The fifteen most sensitive ILs in descending order are Praia do Indio, Maraiwatsede, Tuwa Apekuokawera, Apipica, Tadarimana, Cana Brava/Guajajara, Jarudore, Recreio/São Félix, Urucu/Juruá, Governador, Urubu Branco, Las Casas, Bacurizinho, Rodeador, and Lagoa Comprida (Table 2).

The combined influence of EX and SE, the potential impact index (PI), varied from 0.00077 to 0.69. The PI values of ILs in the 1st quantile (the least impacted ILs) varied from 0.00077 to 0.018. The PI values of ILs in the 4th quantile (the most impacted ILs) varied from 0.27 to 0.69. As to EX and SE, the PI index is higher in ILs in the region of the Arc of Deforestation and below, and in the state of Roraima (Fig. 3C). The fifteen ILs with the highest PI index in descending order are Tuwa Apekuokawera, Maraiwatsede, Lagoa Comprida, Praia do Indio, Urucu/Juruá, Rio Pindaré , Cana Brava/Guajajara, Las Casas, Jarudore, Governador, Arariboia, Geralda Toco Preto, Bacurizinho, Umutina, and

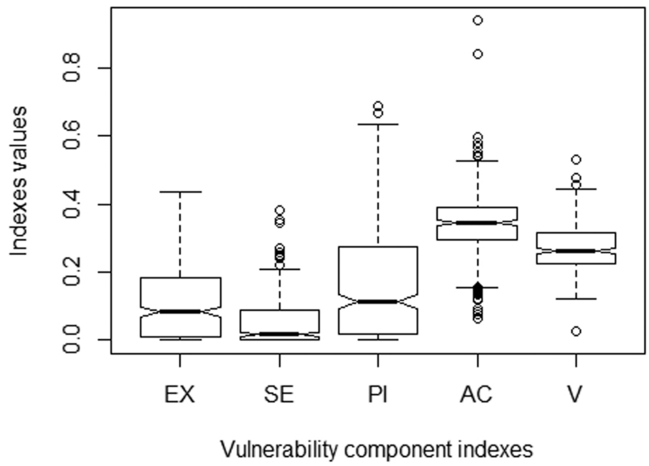

Fig. 4. Boxplots of the final indexes of exposure, sensitivity, adaptive capacity, potential impact, and vulnerability. The whiskers represent the highest and lowest values of the distribution, excluding outliers. Data beyond the end of whiskers are outliers and plotted as dots.

Tadarimana (Table 2).

Overall, our results demonstrate a strong relationship between the environmental threats affecting Amazonian ILs internally and externally, that is, SE and EX (Spearman $r = 0.79$, $p < 0.0001$) (Fig. A.1A). This result is in agreement with the results found by Rorato et al. (2021) for ILs in the Brazilian Amazon, as well as with the results found by Iwamura et al. (2016), a sustainability assessment, which indicates that land conversion around titled ILs in the Ecuadorian Amazon are projected to decrease vegetation cover within ILs. It highlights the need for policy strategies to combat and control environmental threats within and around ILs in the Amazon. We argue that, without the effective control of the environmental agencies over the activities developed around the ILs, it is difficult to contain the progress of environmental degradation over these territories.

Regarding exposure and sensitivity, both the most exposed and the most sensitive ILs are located in areas of consolidated settlement (Arc of Deforestation or older frontier areas). The sensitivity is lower than the exposure, i.e. the areas surrounding ILs are more environmentally degraded than the interior of the ILs. This could be expected given the protected status of ILs. The high values of EX, SE, and PI in regions of more consolidated occupation can be explained by the fact that the facilitation of invasion and exploitation of ILs resources takes place through the existing infrastructure network (Aguiar et al., 2007; Red Amazónica de Información Socioambiental Georreferenciada – Raisg, 2020; Ferrante et al., 2020; Schielein and Börner, 2018). Within these regions, smaller ILs are generally more exposed and sensitive, in line with the assumption in the study of Lapola et al. (2020) reflected by their choice of IL size as an indicator of resilience.

3.2. Adaptive capacity

The adaptive capacity index (AC) varied from 0.064 to 0.94, varying widely over the Amazon region (Fig. 3D). The AC values of the ILs in the 4th quantile (the ILs with the highest AC) varied from 0.39 to 0.94. The AC values of the ILs in the 1st quantile (the ILs with the lowest AC) varied from 0.064 to 0.30. The fifteen ILs with lowest AC values are, in ascending order, Tanaru, Cobra Grande, Jauary, Tuwa Apekuokawera, Praia do Mangue, Vista Alegre, Maracaxi, Estação Parecis, Jacareúba/Katauixi, Igarapé Taboca do Alto Tarauacá, Ituna/Itatá, Menkü, Murutinga/Tracaja, Paukalirajausu, and Pirititi (Table 2).

Two ILs stand out in relation to the high adaptive capacity they have: Alto Rio Negro (AM) with AC = 0.94 and Parque do Xingu (MT) with AC = 0.84. The Alto Rio Negro IL presents values far above the median for most AC indicators when compared to all ILs, as follows (median ± *sd*): number of projects = 1 (0.03 ± 0.09), number of Indigenous organizations = 1 (0.04 ± 0.10), funding amount = 0.84 (0.01 ± 0.14), institutional arrangement = 0.89 (0.05 ± 0.10), LPI = 0.97 (0.79 ± 0.27), and literacy = 0.75 (0.66 ± 0.33). The Parque do Xingu IL, in turn, also has relatively high values for most AC indicators compared to median, except to literacy: number of projects = 0.84, number of Indigenous organizations = 0.73, funding amount = 0.84, institutional arrangement = 1, LPI = 0.90, and literacy = 0.46. Following are the ILs São Marcos - RR, Vale do Javari, Raposa Serra do Sol, Menkragnoti, Kayapó, Parque do Tumucumaque, Uaç á, Rio Paru DEste, Waiãpi, Jumina, Yanomami, Andirá-Marau, Galibi, and Kraolandia ranging between AC = 0.50 and AC = 0.59.

Our results demonstrated a significant, although weak, relationship between the AC and PI index (Spearman $r = -0.19$, $p < 0.00027$) (Fig. A.1B). The negative relationship indicates that ILs with a high PI (i.e., the sum of SE and EX) are likely to have low AC, in line with our framework (McCarthy et al., 2001; Schneider et al., 2007) and assumptions that ILs with low adaptive capacity could be more susceptible to internal and external environmental threats. However, we highlight that some ILs classified with high AC values also showed high SE index values. Such as the ILs Yanomami, Kraolandia, Krikati, Xerente, Pareci, Parque do Araguaia, Funil, São Marcos - MT, Bakairi, Porquinhos, Merure, Parabubure, Pimentel Barbosa, and Kanela. With the exception of the IL Yanomami, which is internally affected by illegal mining and located in the North of Roraima and Amazonas states, the other ILs are located in the Arc of Deforestation region, characterized by intense occupation and environmental degradation. These results indicate that even ILs that have a stronger articulation with the majority society, a higher capacity to self-organize and to raise funds, and have their lands regularized, face constant environmental threats within their territories; requiring State and institutional support through enforcement actions, punishments and policies to control and combat these threats.

The AC component showed larger variability than EX and SE (Fig. 4) (including outliers), indicating that the Indigenous Lands of the Amazon are highly heterogeneous in their organization and socioeconomic conditions. While for some ILs, people have more capacity for self-organization and articulation with other sectors of society, allowing them access to various resources (such as projects and incomes); other ILs still lack this type of articulation and have low access to these resources. In general, there seems to be a trend that large ILs have high AC values. We found a significant ($p < 0.0001$) positive correlation between the area of ILs and the AC indicators number of projects (Spearman $r = 0.33$), number of Indigenous organizations (Spearman $r = 0.29$), financing value (Spearman $r = 0.42$), LPI (Spearman $r = 0.54$) and institutional arrangement (Spearman $r = 0.42$). Regarding the indicators related to the development of projects in the ILs, a possible explanation would be the fact that the larger ILs have been demarcated for a longer time and their Indigenous populations have a longer history of interaction with the majority society, in addition to having a greater number of Indigenous organizations that provide access to partners who develop and finance projects in these ILs.

3.3. Vulnerability

The ILs most vulnerable to environmental threats are those that present a high potential impact and a low adaptive capacity. The vulnerability index (V) of Amazonian ILs over the period 2001–2019 varied from 0.025 (Alto Rio Negro IL) to 0.53 (Tuwa Apekuokawera IL). The V values of ILs in the 1st quantile (the least vulnerable ILs) varied from 0.025 to 0.22. The V values of ILs in the 4th quantile (the most vulnerable ILs) varied from 0.31 to 0.53. In general, vulnerable ILs are most concentrated in the Arc of Deforestation region and below, as well as in the states of Pará, Amazonas, and Roraima (Fig. 3E). The median values of exposure and sensitivity, in general, are higher in the Arc of Deforestation than in Roraima, except for the indicators of roads and

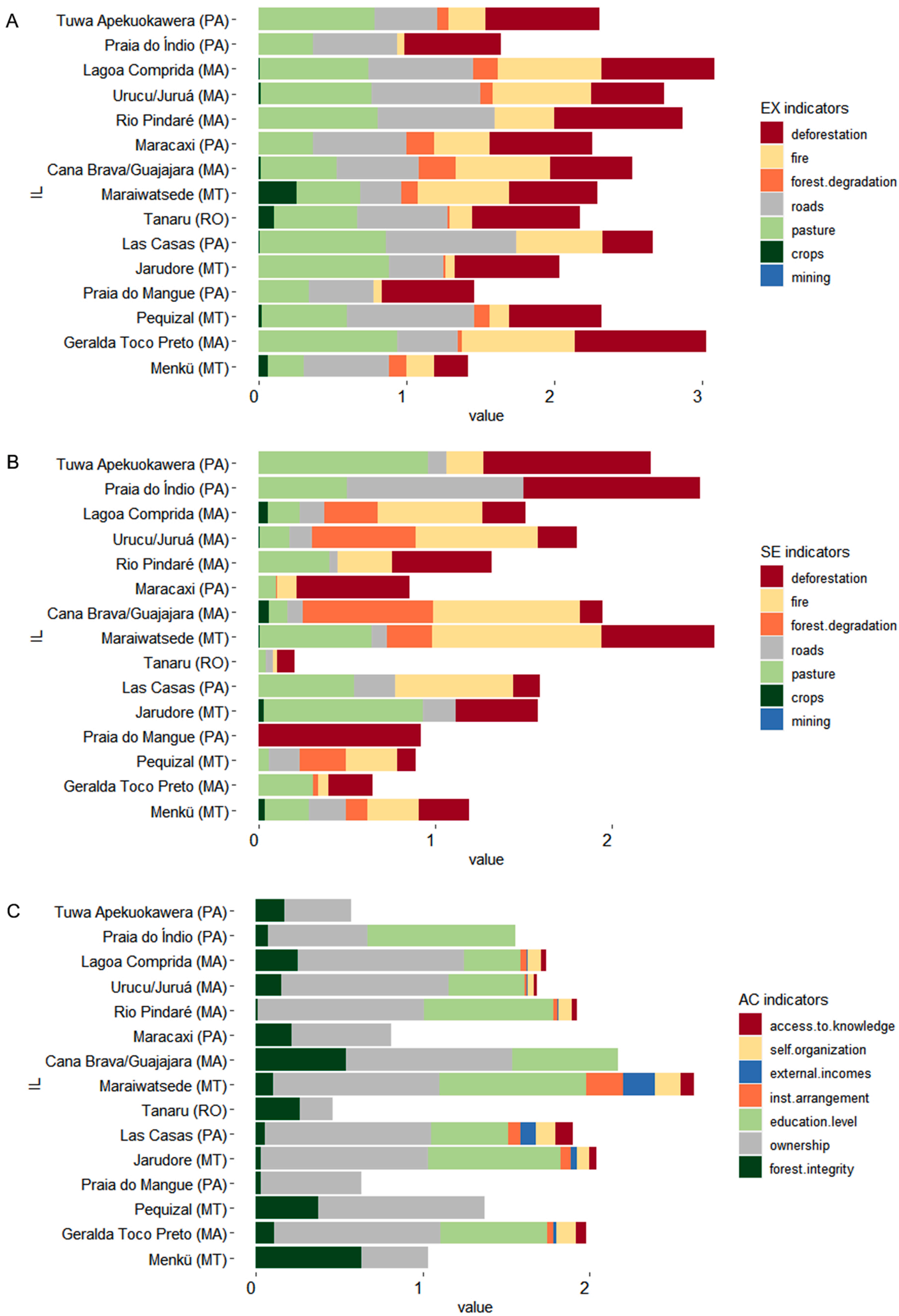

Fig. 5. Values of exposure (A), sensitivity (B) and adaptive capacity (C) indicators for the 15 most vulnerable Indigenous Lands, starting with the most vulnerable at the top.

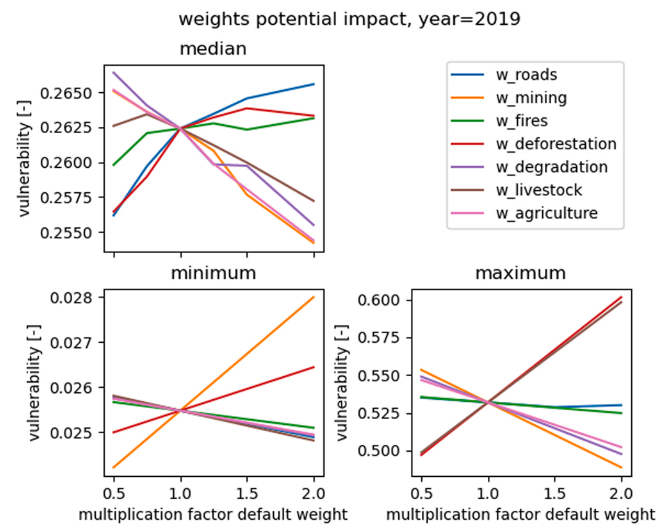

Fig. 6. The OAT sensitivity analysis results for the weights of the potential impact indicators (i.e. EX plus SE indexes) by 2019. The graphs show the influence of changes in the weights of the indicators on the median, the maximum and minimum value of the Vulnerability index.

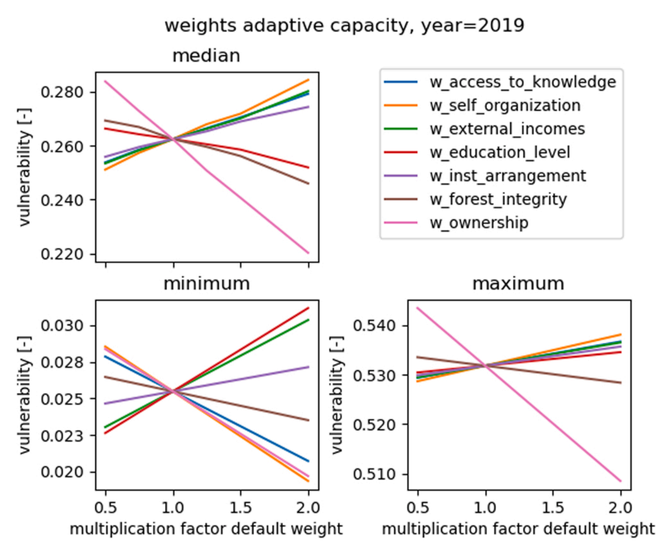

Fig. 7. The OAT sensitivity analysis results for the weights of the adaptive capacity indicators by 2019. The graphs show the influence of changes in the weights of the indicators on the median, the maximum and minimum value of the Vulnerability index.

fires. For the indicator roads, the median sensitivity of ILs is 0.13 in Roraima, while only 0.02 in the Arc of Deforestation. As for the fire indicator, the median sensitivity is 0.12 in Roraima, while only 0.09 in the Arc of Deforestation.

The fifteen Amazonian ILs most vulnerable to environmental threats in descending order are Tuwa Apekuokawera, Praia do Indio, Lagoa Comprida, Urucu/Juruá, Rio Pindaré , Maracaxi, Cana Brava/Guajajara, Maraiwatsede, Tanaru, Las Casas, Jarudore, Praia do Mangue, Pequizal, Geralda Toco Preto, and Menkü (Table 2). Among these most vulnerable ILs, the main exposure threats are deforestation, the proximity of roads, the presence of pastures, and the occurrence of fires (Fig. 5A). The latter only for some ILs; Praia do Indio, Jarudore, and Praia do Mangue are barely exposed to fire. The sensitivity component has more variation in the contribution of indicators to the total component value than the exposure component (Fig. 5B). Most prominent are deforestation and the presence of pastures within these ILs. Interestingly, none of the most vulnerable ILs have records of occurrence of mining activity inside or in the buffer zone (Fig. 5A,B). Regarding adaptive capacity, six of the fifteen most vulnerable ILs had a value of zero for the indicators access to knowledge, self-organization, external incomes, institutional arrangement and literacy; among them is the most vulnerable IL, Tuwa Apekuokawera (Fig. 5C).

Within these fifteen, the ILs Las Casas, Lagoa Comprida, Cana Brava/Guajajara, and Urucu/Juruá are among the fifteen highest in terms of EX and SE values too, but not among the fifteen lowest AC values. Tuwa Apekuokawera, the most vulnerable IL, is among the fifteen highest in terms of EX and SE values too, and among the fifteen lowest AC values. Its land regularization process has not yet been concluded, being only Delimited. In related work, the Tuwa Apekuokawera IL is considered highly vulnerable to changes induced by climate change (Lapola et al., 2020). The other two Amazonian ILs with high vulnerability to undergo changes related to climate change, according to that study, are Uru-Eu-Wau-Wau and Paraná do Arauató, which in our evaluation present moderate Vulnerability (V = 0.29 (3rd quantile) and V = 0.26 (2nd quantile), respectively). While Uru-Eu-Wau-Wau IL has high exposure (EX = 0.26), moderate sensitivity (SE = 0.02) and high adaptive capacity (AC = 0.39); Paraná do Arauató IL has moderate exposure (EX = 0.03), sensitivity (SE = 0.05) and adaptive capacity (AC = 0.32).

In general, we argue that the results of our implementation of the IPCC's vulnerability framework are in line with what we might expect for some ILs located in regions of intense environmental degradation, as is the case for the ILs in the state of Maranhão (Junior et al., 2020). Among 19 ILs in the state of Maranhão (in the Legal Amazon region), 16 are classified with a high vulnerability index (4th quantile).

Among them are ILs that shelter isolated Indigenous peoples (groups that refuse contact with non-indigenous peoples or were never officially contacted by FUNAI) and Indigenous peoples of recent contact (contacted by FUNAI not so long ago), such as the ILs Caru, Arariboia, Awá, Cana Brava/Guajajara, and Alto Turiaçu. It is believed that the isolated position of the former group is a consequence of negative experiences with other people suffered by them in the past (Vaz, 2013; Brackelaire, 2006; Ferreira Amorim, 2016). The isolated Indigenous people of the IL Awa (V = 0.37), belonging to the Awá Guajá ethnic group, are considered the most vulnerable Indigenous people in the world by the Survival International Foundation. Besides, the ILs Xikrin do Rio Catete (PA) (V = 0.33) and Urubu Branco (MT) (V = 0.37) also sheltering isolated Indigenous peoples and are classified as highly vulnerable to environmental threats.

3.4. Sensitivity Analysis

Our vulnerability assessment has proven robust (Figs. 6 and 7). Very small changes in the vulnerability index are observed for substantial changes in the indicators' weights (i.e., −50%, +50%, and +100%) of PI and AC components, respectively. Among the indicators in the PI component, the median of the vulnerability index is most sensitive to changes in the weights of the mining (maximum variation from ≈ 0.2540 to ≈ 0.2650), deforestation (from ≈ 0.2563 to ≈ 0.2635), and livestock (from ≈ 0.2575 to ≈ 0.2632) indicators, which also have the highest weight values attributed by the experts. For indicators of the AC component, the median of vulnerability index is most sensitive to variations in the weights of the indicators of the regularization status of ILs (land ownership) (maximum variation from ≈ 0.220 to ≈ 0.285), and self-organization (from ≈ 0.255 to ≈ 0.285), also the indicators with the highest weights.

3.5. Changes in exposure and sensitivity of ILs between the periods 2001–2010 and 2011–2019

Most Amazonian ILs had larger exposure, sensitivity, and consequently potential impact in period *t2* = 2011–2019 than in period

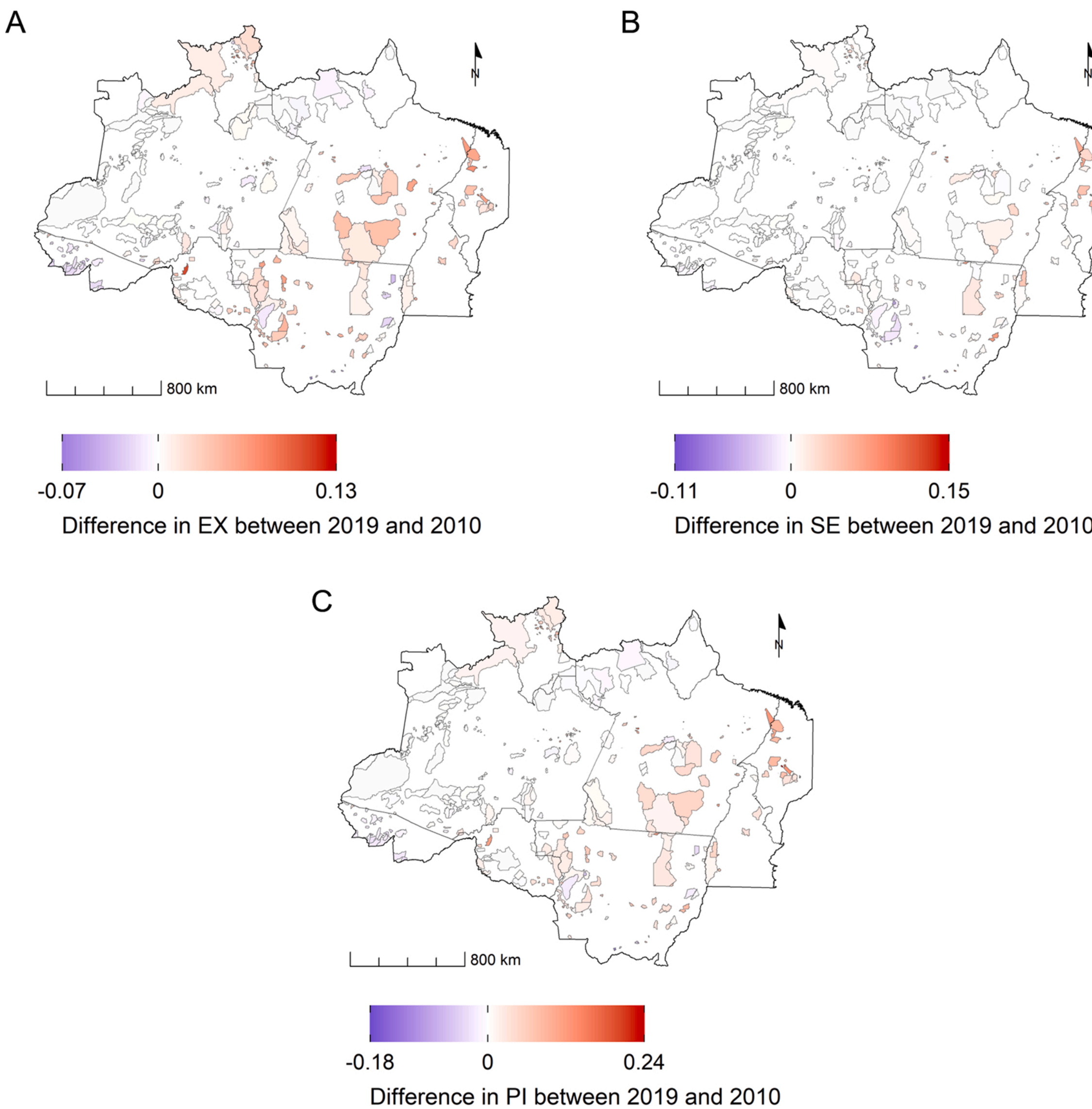

Fig. 8. The difference between the exposure (A), sensitivity (B), and potential impact (C) indexes between the periods 2001–2010 (*t1*) and 2011–2019 (*t2*) (i.e. difference = index *t2* - index *t1*). Because of the lack of mining data available for the first period, mining was not considered in the calculation of these indexes. Negative values mean that the index is higher in period *t1*, while positive values represent that the index is higher in period *t2*.

t1 = 2001–2010 (Figs. 8A–C, 9; Table 3). Both the EX (Wilcox v = 17367, $p < 0.0001$) and SE (Wilcox v = 22857, $p < 0.0001$) differ significantly between the two periods. In total, 283 ILs (73.9% of the total) showed to be more exposed to environmental threats in period *t2* than in period *t1* (Figs. 9 and A.2). Similarly, 248 ILs (64.8%) showed to be more sensitive in period *t2* (Figs. 9 and A.3). And, 205 ILs (53.5%) presented both higher exposure and sensitivity in period *t2* than in period *t1* (Fig. 9). The fifteen ILs with the largest increase in PI for the period *t2* are: Urucu/Juruá, Bragança-Marituba, Lagoa Comprida, Rodeador, Krahô-Kanela, Maracaxi, Cana Brava/Guajajara, Terena Gleba Iriri, Alto Rio Guamá, Karipuna, Las Casas, Rio Jumas, Awa, Muduruku-Taquara, and Boqueirão.

Our results suggest a trend of increasing exposure and sensitivity to environmental threats for most Amazonian ILs after 2010. This is in line with other work: in an analysis of environmental governance in the Amazon from 1950 to the present day, Ribeiro Capobianco (2019) highlights that the period from 2003 to 2009 was characterized by the resumption of the role of the Federal Government with strong integrated action to combat environmental degradation in the Amazon. On the other hand, the period from the beginning of 2010 to the present day is characterized by reduced protagonism and abandonment of the socio-environmental agenda by the Federal Government.

Besides, in last years, there has been a dismantling of the country's environmental policy (Abessa et al., 2019; Pereira et al., 2019, 2020; Vale et al., 2021). Profound structural and regulatory changes, coupled with a severe shortage of financial resources and personnel, have drastically reduced environmental agencies' operational capacity in the country (Artaxo, 2019; Escobar, 2018; Abessa et al., 2019; Pereira et al., 2019; Vale et al., 2021). After the dismantling of surveillance policies, illegal mining within Indigenous lands has expanded significantly in recent years and poses a major threat to the environment and traditional peoples in the region (Rorato et al., 2020; Diele-Viegas et al., 2020; Siqueira-Gay and Sánchez, 2021). Most ILs known to be impacted by illegal mining within their boundaries and surroundings (Rorato et al., 2020; Siqueira-Gay et al., 2020) have a medium to high vulnerability in our assessment, such as Yanomami (V = 0.26), Kayapó (V = 0.27), Munduruku (V = 0.24), Sawré Muybu (Pimental) (V = 0.30) and Sararé (V = 0.35).

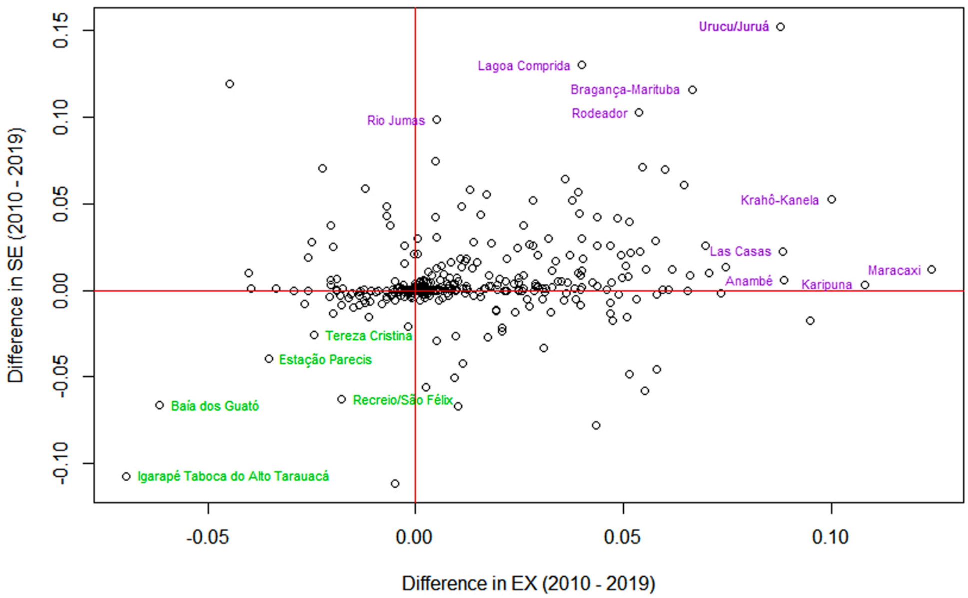

Fig. 9. Scatter plot of the difference of exposure indexes between periods t1 and t2 and of sensitivity indexes between periods t1 and t2 (i.e. difference = index t2 - index t1). Negative values mean that the index is higher in period t1, while positive values represent that the index is higher in period t2. Name of Indigenous Lands at the extremes in purple (left) and green (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Mean, median, and standard deviation of the exposure and sensitivity indexes for periods t1 (2001–2010) and t2 (2011–2019).

	Exposure		Sensitivity		Potential impact	
	t1	*t2*	*t1*	*t2*	*t1*	*t2*
mean	0.086	0.098	0.039	0.044	0.125	0.142
median	0.061	0.075	0.012	0.013	0.079	0.103
sd	0.089	0.101	0.057	0.061	0.131	0.147

3.6. Policy recommendations

Our results have quantified the vulnerability of Amazonian ILs. The quantification can be used to prioritize help to certain ILs, and the understanding of the contribution of the underlying dimensions can serve as input to direct public policies, possible according to the profile of each IL in relation to its AC, EX and SE. In this sense, our recommendation is that public policies be oriented towards the improvement of all components, that is, to increase AC and reduce EX and SE. We see the largest opportunity in the reduction of EX, because 1) the indicator values are generally higher than for SE, and 2) because the largest threats are more uniform over the most vulnerable ILs (Fig. 5), allowing for uniform strategies to fight them, instead of, more complex, tailored strategies per IL (profile).

A strategy to potentially follow is to rescue and strengthen the National Policy for Environmental and Territorial Management of Indigenous Lands (PNGATI) (Brazilian Executive Power, 2012) that was abandoned in recent years, expanding its implementation to all ILs in the Amazon, as well as their buffer zones. PNGATI was developed to promote Indigenous peoples' empowerment in relation to the environmental and territorial management of their territories, with autonomy, but with active support from the State. Among the several targets of PNGATI are the strengthening of Indigenous organizations, guaranteeing Indigenous participation in PNGATI governance; training of Indigenous populations regarding the environmental and territorial management of ILs and the recovery of degraded areas; and supporting for sustainable and economic Indigenous initiatives that generate alternative livelihoods for these peoples.

PNGATI has already shown positive results, such as the creation of a regulatory framework that reiterates the exclusive use of ILs by Indigenous peoples, as well as strengthening the organizational empowerment of these peoples (van Velthem Linke et al., 2020), and has been characterized as an important tool in the planning and use of Indigenous lands, fundamental for sustainability (Júnior et al., 2021). Some positive examples within the scope of PNGATI are the case of its implementation in ILs in the state of Mato Grosso with the improvement of territorial monitoring techniques and sustainable management of agroforestry products (Jakubaszko, 2020); the reforestation actions developed in IL Maraiwatsede (MT); the management of turtles in the lower Marmelos River (AM); the encouraging sustainable production of nuts by the Cinta Larga (RO) people; and the training of countless Indigenous brigade members to fight and manage fires (National Indian Foundation – FUNAI, 2021).

Regarding the adaptive capacity of Amazonian Indigenous peoples, we highlight here the role of Indigenous organizations, since it was through the creation of them, from the end of the 1980s, that the Indigenous peoples began to have greater autonomy to deal with the different spheres of majority society and began to articulate their demands (Ricardo, 1998). We also draw attention to the importance of partnerships established between Indigenous organizations and partner institutions, whether private, governmental, or non-governmental, to develop local projects. Through this articulation, the conditions and potential for environmental preservation and sustainable development of Indigenous lands in the Amazon have emerged in recent decades (Albert, 2019). It is necessary to increase governmental and non-governmental support to Indigenous organizations, expanding their access to different opportunities for socio-environmental programs, projects and resources; especially in ILs with low AC in combination with high EX and/or SE (Fig. 3D and Table 2). As such, our results can provide prioritization information for project development/granting and targeting public policies for the ILs.

It is also important to emphasize the current vulnerability of Indigenous peoples in Brazil to legal attacks that threaten their rights. Among these attacks, we can highlight bill 191/2020, which would open ILs to agribusiness, cattle raising, dams and mining (Rorato et al., 2020); as well as bill 490/2007, approved by the Chamber of Deputies, which allows the revocation of ILs created from 1988 (Ferrante and Fearnside, 2021). Such bills, if approved, represent an unprecedented setback for the rights conquered by Brazilian Indigenous peoples and could substantially aggravate the environmental vulnerability of ILs and of Indigenous populations as a whole. It is imperative that such proposed laws are discarded and policies that protect the Indigenous peoples of Brazil and their lands are re-established and strengthened.

Finally, government action is of paramount importance to curb the recent increase in Amazonian ILs' exposure and sensitivity to environmental threats. The strengthening of the FUNAI and IBAMA (Brazilian Institute of the Environment and Renewable Natural Resources) agencies and the resumption of policies to control and combat illegal activities are fundamental to reduce the environmental vulnerability of ILs and safeguard the rights of Indigenous peoples.

4. Limitations and future work

Concerning the vulnerability framework design, the most recent IPCC report about vulnerability assessment (Field et al., 2014) presents some changes in relation to the previous reports, adopted in this study (McCarthy et al., 2001; Schneider et al., 2007). The most important change is that vulnerability is defined as an intrinsic property of the system and is, as such, composed of sensitivity and adaptive capacity only (Sharma and Ravindranath, 2019); exposure is treated as an external component. In the present study, we argue the importance of maintaining exposure as a component of vulnerability, as exposure to threats seems to have a great influence on the threats that advance on Amazonian ILs. We assume that by not considering the processes around these territories, we would neglect an important component in the emergence of their vulnerability.

In general, synthetic indexes, such as PI and V, are useful for summarizing information from several components. Despite the importance of these synthetic indexes, we highlight the need of evaluating the components separately, here SE, EX, and AC. Looking at these components can be more informative and more appropriate to guide the design of appropriate public policies since they are more understandable as they contain less information and more variation than the synthetic indexes PI and V (Fig. 4).

Although our AC indicators are related to the Indigenous peoples of each IL, our analysis is at the level of Indigenous lands instead of Indigenous people, making the vulnerability assessment indirect. The source of this limitation is the lack of data related to Indigenous populations. The most complete compilation of socio-demographic data of the Brazilian Indigenous population was carried out in 2010, during the last Demographic Census in the country. Furthermore, these outdated data do not exist for all analyzed ILs. Thus, we chose not to include the size of the Indigenous population and other variables related to socio-economic dimensions in the AC component, despite their importance. We emphasize the need for a systematic compilation of the Brazilian Indigenous population's socio-demographic data to enable coherent assessments of the vulnerabilities of these peoples.

Many other characteristics of Indigenous peoples could be included in the AC component, within the human resources dimension, as important characteristics for their adaptive capacity, such as cultural knowledge, forms of organization and social structures, ecological knowledge, traditional management practices, forestry and agriculture, and demographic aspects (number of people, age structure, level of education, and number of isolated groups) (Moss et al., 2001; Nguyen et al., 2016; Jamshidi et al., 2019). However, there are no systematic and sufficient data to characterize these factors for Indigenous peoples in Amazon, despite their importance. The inclusion of these factors can be done in future case studies focused on one or a few ILs so that it is possible to compile such variables and relate them to the changes in the adaptive capacity of Indigenous populations.

We recognize the limitation of the lack of data for the occurrence of mining activities in the first period *t1* (2001–2010); making time comparison with this indicator unfeasible. In addition, in any indicator-based approach, the selection of indicators is arbitrary. In this sense, to assess the vulnerability of the Amazon Indigenous Lands, other researchers could have chosen other threats and other ways of representing the indicators. Generally, the choice of variables is strongly related to data availability.

Concerning future work, spatial simulations can be an excellent way to explore the potential of different strategies to reduce the environmental vulnerability of the Amazon region and ILs. In these simulations, alternative scenarios of policies to control and combat environmental threats and a contrasting scenario of loosening legislation could be explored. The challenge herein is what subsets of the environmental system to include, e.g. in terms of land use and climate change projections.

5. Conclusion

The present study was a pioneer in operationalising the IPCC vulnerability framework to investigate the environmental vulnerability of Indigenous Lands. Our first research question was: What is the environmental vulnerability of ILs in the Amazon? We found that the environmental vulnerability of Amazonian ILs in the period 2001–2019 ranged from 0.025 to 0.53. In general, ILs with high vulnerability are concentrated in the Arc of Deforestation region and South of it, as well as advancing in Pará and Roraima states. The state with the most highly vulnerable ILs (84% of ILs) is Maranhão. The main source of spatial variation in vulnerability, especially outside of the Arc of Deforestation, is the adaptive capacity. Our results have proven to be robust in relation to the weights assigned to the indicators.

Our second research question was: How have the exposure and sensitivity of Amazonian ILs to environmental threats changed in the past ten years? We found that the exposure and sensitivity of ILs are increasing; in 2011–2019 around 73.9% of all ILs were more exposed to environmental threats, while 64.8% of all ILs showed to be more sensitive compared to 2001–2010. Furthermore, our results demonstrate a strong relationship between the environmental threats that affect Amazonian ILs internally and in their surroundings, illustrating the large pressure exerted on ILs by external processes and the need for policies aimed at control and inspection of the activities in the vicinity of ILs.

International treaties aimed at environmental conservation, reducing human populations' vulnerability, and targeting sustainable development recognize the importance of joint social and environmental agendas to face global change challenges. The Indigenous peoples of the Amazon and their territories represent keys human-environment systems of global relevance to achieve sustainability goals. There is a promising potential in the empowerment of Indigenous peoples and the improvement of their adaptive capacity: reconciling the sustainable environmental management of their territories with viable alternative livelihoods for these peoples. The adoption of public policies by the State, such as combating and controlling illegal activities within and around ILs, and strengthening PNGATI play a fundamental role in achieving this goal and reducing the environmental vulnerability of Amazonian Indigenous Lands.

CRediT authorship contribution statement

Conceptualization, A.C.R., J.A.V., G.C., and M.I.S.E.; Methodology, A.C.R., J.A.V., G.C., and M.I.S.E.; Formal analysis, A.C.R. and J.A.V.; Data curation, A.C.R.; Writing – original draft preparation, A.C.R.; Writing – review & editing, A.C.R., J.A.V., G.C., M.I.S.E. and M.C.A.P; Supervision, J.A.V. and M.I.S.E. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

See: Table A.1, Figs. A.1–A.4.

Table A.1
Stages of the recognition process of Indigenous Lands in Brazil.

Stage	Description
In study	Conducting anthropological, historical, land, cartographic and environmental studies, which support the identification and delimitation of Indigenous Land.
Delimited	Lands that had their studies approved by the Funai Presidency, with their conclusion published in the Official Gazette of the Union and the State, and that are in the administrative contradictory phase or under analysis by the Ministry of Justice, for a decision on the issuing of a Declaratory Ordinance traditional Indigenous possession.
Declarated	Lands that obtained the expedition of the Declaratory Ordinance by the Minister of Justice and are authorized to be physically demarcated, with the materialization of the landmarks and georeferencing.
Homologated	Lands that have their materialized and georeferenced limits, whose administrative demarcation was approved by Presidential decree.
Regularized	Land that, after the homologation decree, was registered in a Notary's Office in the name of the Union and in the Federal Heritage Secretariat.
Forwarded with Indigenous Reserve	The Indigenous Reserve constitutes a differentiated category of Indigenous Land, mainly due to the way it is acquired by the State and intended for the Indigenous population. In this way, this category is out of the stages of the recognition process cited above. The Indigenous Reserves are areas that are in the administrative process of acquisition by the Union (direct purchase, expropriation or donation) intended for the possession and occupation of Indigenous peoples; where they can live and obtain means of subsistence, with the right to enjoy and use natural resources, guaranteeing the conditions for their physical and cultural reproduction.

*Source: FUNAI (*National Indian Foundation – FUNAI, 2019b).

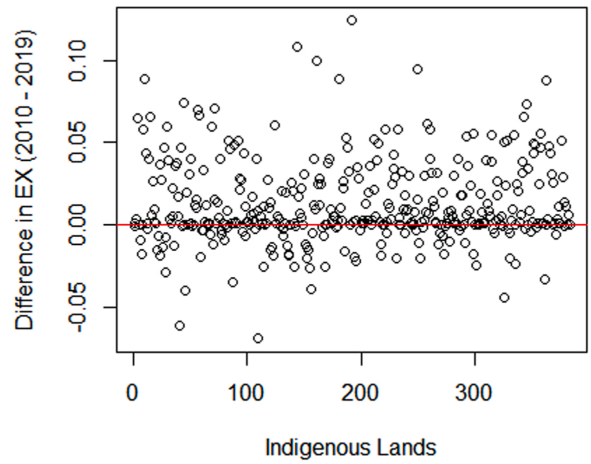

Fig. A.2. Scatter plot of the difference of exposure indexes between periods t1 and t2 (i.e. difference = index t2 - index t1). Negative values mean that the index is higher in period t1, while positive values represent that the index is higher in period t2.

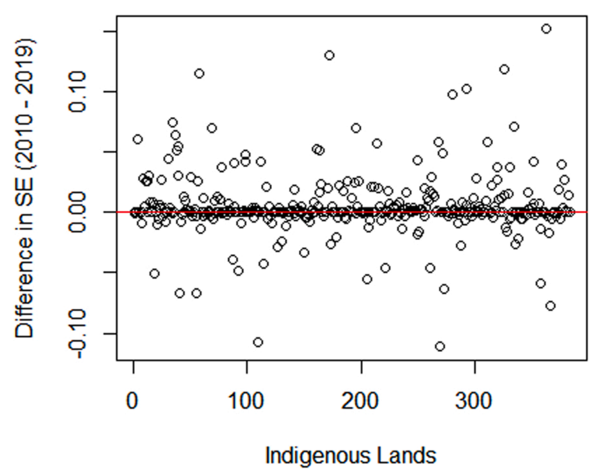

Fig. A.3. Scatter plot of the difference of sensitivity indexes between periods t1 and t2 (i.e. difference = index t2 - index t1). Negative values mean that the index is higher in period t1, while positive values represent that the index is higher in period t2.

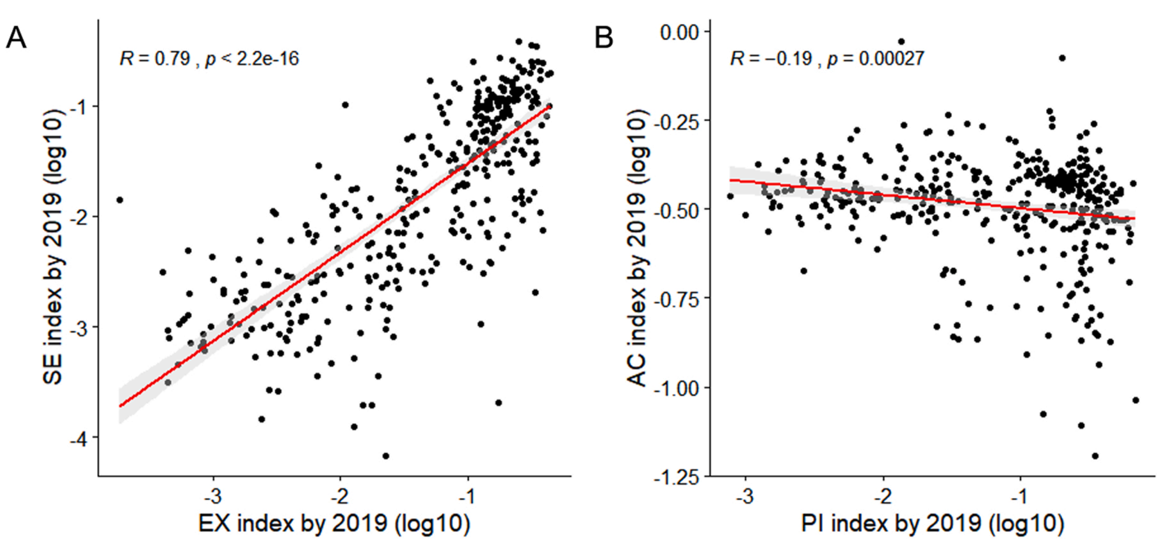

Fig. A.1. Scatter plot of the final indexes of exposure and sensitivity (A), and potential impact and adaptive capacity (B). The regression line in red and the confidence interval of 95% in grey. The indexes are displayed on a logarithmic scale. Indigenous lands are represented as points.

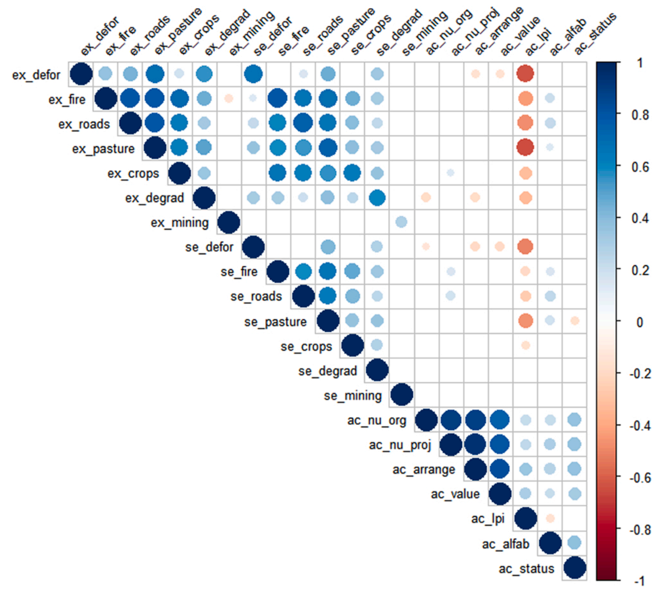

Fig. A.4. Correlogram of EX, SE and AC indicators. Spearman correlation and significance level of p = 0.01. The absence of a circle means that the relation is not significant.

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