Disrupting a socio-ecological system: How could traditional ecological knowledge be the key to preserving the Araucaria Forest in Brazil under climate change?

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Research Article

Keywords: Araucaria Forest system, Climate change, Ecosystem services network, Ethnoecology, Mixed Ombrophilous Forest, Pinhão management

Posted Date: May 31st, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1569478/v1

Version of Record: A version of this preprint was published at Climatic Change on January 16th, 2023. See the published version at https://doi.org/10.1007/s10584-022-03477-x.

Abstract

Socio-ecological systems (SESs) hinge on human groups and ecosystems, promoting interdependence and resilience to environmental disturbances. Climate change effects propagate from organisms to biomes, likely influencing SESs. In southern Brazil, the Araucaria Forest is a typical SES due to the historical interaction between humans and biodiversity. Thus, we empirically and theoretically evaluated how climate change could disrupt this system by interviewing 97 smallholders and assessing their traditional ecological knowledge (TEK). We evaluated and measured the socioeconomic impact of the araucaria's (*Araucaria angustifolia*) nut-like seed (pinhão) trade and the ethnoecological knowledge about climate change, as well as generated an ecosystem services network. We used these empirical data with a projected loss of 50–70% of the Araucaria Forest due to climate change to quantify the risks of the potential disruption of this SES. We found evidence that to avoid the disruption of the Araucaria Forests, it is paramount to value TEK holders, safeguard the historical socio-ecological interaction, and promote non-mutually exclusive measures in an integrative response to maintain the resilience of this forest to future disturbances.

1. Introduction

Climate change effects have been widely described throughout all ecosystems (Malhi et al. 2020), from organism to biome levels (Parmesan 2006), affecting the genetics of organisms (e.g., allelic diversity) and the integrity of biomes, such as ecological resilience to disturbances (Bellard et al. 2012). These threats also impinge on socio-ecological systems (hereafter SESs), which consist of the integration of local human groups with ecosystems, promoting reciprocal feedbacks, interdependence, and resilience (Folke et al. 2010). These local human groups commonly rely on interacting with natural assets and could be represented in Brazil by Indigenous people, local communities (e.g., *ribeirinhos*, *caiçaras*), or even small landowners (De Souza et al. 2006; Fatorić and Chelleri 2012; Gomes et al. 2018; Tagliari et al. 2021a). These groups are characterized as holding traditional ecological knowledge (hereafter TEK): a long-term experience based on observation, use, and management of natural resources, which offers a basis for the adaptation and resilience of ecosystems to environmental disturbances, such as climate change (Ladio 2017).

Ecosystems with continuous interactions between plants and peoples are examples of SESs. For instance, enduring human-plant interactions in the Neotropics contributed to enhancing plant domestication and food security across Amazonia (Levis et al. 2018) and the Araucaria Forest in southern Brazil (Cruz et al. 2020). The Araucaria Forest, also known as Araucaria Mixed Forest, is an emblematic SES in the subtropical Atlantic Forest region (Tagliari et al. 2021a). The main plant species in this ecosystem is *Araucaria angustifolia* (Bertol.) Kuntze, a tree with a candelabra aspect that is popularly known as araucaria, critically endangered according to the International Union for Conservation of Nature, and was almost depleted do to extensive and illegal logging in the early to late 20th century (Thomas 2013). The species plays a key ecological role in the ecosystem's functioning due to its nut-like seed called *pinhão*. The nutritious *pinhão* structures the associate vertebrate consumers spatiotemporally

(Oliveira-Filho et al. 2015; Bogoni et al. 2020a). Furthermore, the species is also valuable due to its ancient connection with Indigenous peoples and local communities (Reis et al., 2014; Robinson et al., 2018) that still use and manage *pinhão* (Adan et al. 2016; Quinteiro et al. 2019). Forest management strategies used by human groups over the last 1400 years expanded the Araucaria Forest beyond its natural boundaries, and some of these landscape modifications are still visible (Robinson et al. 2018; Cruz et al. 2020). Currently, the traditional management systems of local smallholders do the following: (i) maintain productive forest fragments (Mello and Peroni 2015); (ii) promote ecosystem services (Tagliari et al. 2019) and temporal food security to local fauna and human groups (Adan et al. 2016; Bogoni et al. 2020a); (iii) preserve cultural, social, and economic dynamics in this SES (Zechini et al. 2018; Tagliari et al. 2021a); and (iv) maintain the functional diversity of araucaria, especially due to the identification of *pinhão* ethnovarieties thanks to TEK holders (Adan et al. 2016; Tagliari and Peroni 2018; Quinteiro et al. 2019). These traditional systems managed by TEK holders also boost positive feedbacks that might expand the Araucaria Forest (Tagliari et al. 2021a). Consequently, araucaria is also classified as a “cultural keystone species” (Garibaldi and Turner 2004), since it plays cultural and socio-ecological roles in southern Brazil (Reis et al. 2014; Adan et al. 2016; Quinteiro et al. 2019). Further, this reinforces the argument that the entire ecosystem behaves as a socio-ecological system (Tagliari et al. 2021a).

However, chronic deforestation, agriculture expansion, and more recently, climate change (Orellana and Vanclay 2018; Castro et al. 2019; Wilson et al. 2019; Marchioro et al. 2020), have been hindering araucaria conservation and the resilience of this SES. To halt biodiversity losses, the creation of protected areas is a cornerstone strategy (Geldmann et al. 2013). Araucaria Forest remnants are still poorly encompassed by the existing protected area network. Recent studies showed that less than 10% of the projected distribution of *A. angustifolia* falls within existing protected areas in present and future climate change scenarios (Castro et al. 2019; Wilson et al. 2019; Marchioro et al. 2020; Tagliari et al. 2021b). From almost 1500 BP until the late 19th century, the Araucaria Forest's natural extent covered an estimated area of 200,000 km² that spanned over Brazil, Argentina, and Paraguay (Nodari 2016). Due to deforestation, no more than 30% of the native remnants remain preserved (Rezende et al. 2018). Moreover, future climate change predictions indicate losses of climatically suitable areas ranging from 60–96.5% compared to the current distribution of the species (Castro et al. 2019; Wilson et al. 2019; Marchioro et al. 2020).

Despite these studies showing the vulnerability of the species to climate change, they all failed to properly indicate what is at stake if climate change disrupts this SES by showing potential losses in ecological, social, and economic aspects. Also, these studies do not consider the historical human-plant interaction and the possibilities to increase resilience to anthropic disturbances (Tagliari et al. 2021a). We aimed to fill this knowledge gap by approaching one of the main actors behind the SES resilience in the Araucaria Forest, local smallholders, which was done for three main reasons. First, we did this because of their TEK related to araucaria use and management (Mello and Peroni 2015; Adan et al. 2016; Quinteiro et al. 2019), which promotes resilience to climate disturbances and functional diversity (Ladio 2017; Tagliari et al. 2021a). Second, Brazilian legislation has a specific protected area category for private property, *Reservas Legais* (legal reserves), which are compulsory protected areas that host almost one-third of all remaining native vegetation in the Atlantic Forest (Metzger et al. 2019). Consequently, TEK holders preserve the majority of the native araucaria remnants because, in southern Brazil, 20% of the land on private properties must be retained as native vegetation (Orellana and Vanclay 2018). Third, communities of poor small farmers might be the most vulnerable groups due to global environmental changes (Pyhälä et al. 2016).

Thus, we depict the aspects within the Araucaria Forest SES that might be at risk due to climate change by looking at a social, economic, ecologic, ethnoecological, and ecosystem services framework. Further, we describe how TEK holders could increase the Araucaria Forest's resilience to climate change. To achieve this framework, we interviewed 97 smallholders throughout the Araucaria Forest. Based on an assessment of their TEK, we systematically describe why this specific human group might be critical to safeguarding the entire Araucaria SES by maintaining its preservation, ecosystem services, araucaria functional diversity (intraspecific diversity), socio-ecological interactions, resilience to disturbances and, especially, by helping it avoid disruption from climate change.

2. Materials And Methods

2.1 Study area

The study was conducted throughout the extent of the original distribution of the Araucaria Forest, where we still find the interaction between human groups and *A. angustifolia* (Fig. 1). We also revisited areas where this human-plant interaction was previously described (see Adan et al. 2016; Tagliari and Peroni 2018; Quinteiro et al. 2019). Historically, the extent of the Araucaria Forest was distributed along highland plateaus at altitudes above 500 m (de Souza et al. 2009), especially in the South Region (states of Paraná, Santa Catarina, and Rio Grande do Sul) and relict patches in the Southeast Region (states of São Paulo, Minas Gerais, and Rio de Janeiro) of Brazil (Quinteiro et al. 2019; Tagliari et al. 2021b).

2.2 Traditional ecological knowledge in the Araucaria Forest system in a nutshell

Different human groups have interacted with the Araucaria Forest over time. Use and management date back to pre-Columbian times, where paleo-Indigenous ethnic groups cultivated *pinhão* (the nut-like seed of araucaria) for subsistence or religious reasons (Reis et al. 2014). Their historical footprint changed the araucaria landscape; archeological data indicate humans influenced the expansion of the forest in the past (Robinson et al. 2018; Cruz et al. 2020). Currently, human groups (i.e., Indigenous people and local smallholders) still rely on Araucaria Forest resources, especially in relation to the use and management of *pinhão* and other plant species, such as *Ilex paraguariensis*, known as *yerba-mate*, a tea-like beverage (Reis et al. 2014), and *Acca sellowiana*, known as *goiabeira-serrana* (Bogoni et al. 2018).

This long-lasting interaction created productive forest management systems that promote “conservation-by-use” (Reis et al. 2018), as well as benefits to human groups, such as (i) economic (*pinhão* trade), (ii) social (cultural identification), (iii) subsistence (food security), and (iv) socio-ecological (environmental services, ecological resilience, and functional diversity of *pinhão*) (Mello and Peroni 2015; Adan et al. 2016; Reis et al. 2018; Zechini et al. 2018; Quinteiro et al. 2019; Tagliari et al. 2021a). The functional diversity of *pinhão* (ethnovarieties) is well described in the literature as an example of TEK held by local smallholders (Adan et al. 2016; Tagliari and Peroni 2018; Quinteiro et al. 2019).

The identification of different ethnovarieties shows aspects of how intricate this human-plant relationship is, indicating food security spatiotemporally, economic dependence (Adan et al. 2016; Quinteiro et al. 2019; Tagliari et al. 2021a)a), and knowledge about araucaria phenology, distribution, threats, uses, or management aspects (Adan et al. 2016; Tagliari and Peroni 2018; Reis et al. 2018; Quinteiro et al. 2019; Bogoni et al. 2020a; Tagliari et al. 2021a). Thus, we gave this human group (i.e., local smallholders and *pinhão* extractors) a semi-structured questionnaire (Table S1). We used the snowball technique (Bernard 2006) to find participants for the semi-structured interviews, where participants recommended people directly involved in araucaria management at the end of the interview. We wanted to include Indigenous peoples as TEK holders, such as the Southern-Jê and Guarani groups, who have shaped the forest composition in southern Brazil (Cruz et al., 2020); however, ethical limitations and legal aspects prohibited us from including them in our study. Our research was approved by the ethics committee at the Universidade Federal de Santa Catarina (CAEE: 86394518.0.0000.0121), following the code of ethics of the International Society of Ethnobiology.

2.3 Socioeconomic data

We defined two distinct strategies to compile socioeconomic data. First, leaning on our semi-structured interviews, we collected information about the interviewees: gender, age, profession, main crops cultivated, time living on the property, how much the *pinhão* trade boosts family incomes, and the amount of *pinhão* (in kg) collected on each property. Second, we used the Sistema IBGE de Recuperação Automática (SIDRA) (https://sidra.ibge.gov.br/home/ipca15/brasil), a public and open-access database from the Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística), to collect several economic indicators and their historical series. We collected two *pinhão* historical series from 2010 to 2019: (i) the amount of *pinhão* collected per year (tons), and (ii) the economic value of the annual trade of *pinhão* (see https://sidra.ibge.gov.br/tabela/289#resultado).

2.4 Ethnoecological knowledge from an ecosystem services approach

To collect ethnoecological data, we also used our semi-structured interviews. We collected information about the use, management, and knowledge of araucaria and its *pinhão* ethnovarieties. Leaning on smallholders' TEK, we collected evidence of the following: (i) ripening period, abundance, size, and color of *pinhão* ethnovarieties; (ii) the *pinhão* ethnovarieties known by each smallholder; (iii) the reproductive phenology and seed production of araucaria trees due to *pinhão* maturation throughout the year; and (iv) the interviewees' perception about the potential impact of climate change on the Araucaria Forest, especially *A. angustifolia*. With this information, we created a framework to describe two aspects of araucaria ethnoecology: (i) the ecosystem services provided by araucaria use and management, targeting four potential ecosystem services (provision, regulation, cultural, and support) (following Bogoni et al. 2020a); and (ii) how *pinhão* ethnovariety use and management confer araucaria functional diversity, socio-ecological food security, and the well-being of smallholders under climate change.

To generate the ecosystem services framework, defined by the Millennium Ecosystem Assessment (MEA) as the "benefits people obtain from ecosystems, promoting human well-being" (Millennium Ecosystem Assessment 2005), we created a binary matrix of *n*-smallholders by *m*-ecosystem services suggested. The total number of ecosystem services perceived by an interviewee about araucaria use and management was given by the sum of all ecosystem services perceived, following Machado et al. (2019). The ecosystem service categories (Bogoni et al. 2020a) and ecosystem services (Millennium Ecosystem Assessment 2005) that affect the well-being of people are the following: (i) provision (resource for human groups, seed predation, seed dispersal, phytodemographic dynamics); (ii) regulation (climate regulation, disease control, insect pest control, natural disaster control); (iii) cultural (e.g., ethnocultural identity, ecotourism, aesthetics, education); and (iv) support (e.g., nutrient cycling, soil formation, primary production, oxygen). We cross-checked the interviewees' perceptions of ecosystem services with the literature to look for actual or possible ecosystem services provided by the Araucaria Forest system.

2.5 Quantifying the disruption of the Araucaria Forest system under climate change

To estimate potential losses due to climate change throughout the Araucaria Forest system, we selected the latest peer-reviewed studies that show the impacts of future climate change on the Araucaria Forest (Table 1). We combined the studies' projections for 2070 (Castro et al. 2019; Wilson et al. 2019; Marchioro et al. 2020; Tagliari et al. 2021b) over the potential losses of climatically suitable areas ($\Delta Sloss$) for araucaria in the future under two climate scenarios — Representative Concentration Pathways (RCP) 4.5 and 8.5 — to propose a baseline of "climate change loss." These four studies used both RCPs (4.5 and 8.5) because this has become common practice in species modelling approaches since they represent optimistic (RCP 4.5) and pessimistic (RCP 8.5) CO_2 emission scenarios (Riahi et al. 2011; Thomson et al. 2011). Thus, we counted all six projections of area loss and divided them by the total amount of projections (*n*-projections) to get a value that represents the potential area loss of the Araucaria Forest system due to climate change (see Eq. 1).

$$\sum RCP\ 4.5\ \Delta S\ loss + \sum RCP\ 8.5\ \Delta S\ loss \Big/ _{nprojections} \quad \textbf{(1)}$$

Table 1
References selected to estimate the potential threat of climate change to the Araucaria Forest system. We only selected peer-reviewed studies that calculated, under the species distribution modelling approach, the potential loss of climatically suitable areas for araucaria by 2070. The Representative Concentration Pathways (RCPs) are CO_2 emission scenarios, where RCP 4.5 is an optimistic scenario that considers an increase mean of 1.4–1.8°C by the late twenty-first century, whereas the RCP 8.5 is a realistic and pessimistic scenario where mean temperatures are expected to increase by 3.7°C by the late twenty-first century (IPCC, 2013).

Reference	**Climatically suitable area loss in 2070 compared to current predictions (%)**			
Climate scenario	**RCP 4.5**	**RCP 8.5**	**RCP 4.5**	**RCP 8.5**
Years	*2050*	*2050*	*2070*	*2070*
Wilson et al. 2019	NA	NA	85.33	96.5
Castro et al. 2019	NA	NA	27.7	60
Marchioro et al. 2020	45	53	53	77
Tagliari et al. 2021b	NA	NA	66.5	89
Projected loss (mean)	–		56.13%	80.62%
Projected average loss	**49%**		**68.37%**	

We defined the average loss of climatically suitable areas to evaluate how climate change could dampen the Araucaria Forest's resilience in the future. Specifically, we evaluated the potential losses of the entire system by looking at the socioeconomic, ethnoecological, and ecosystem services aspects described above.

To quantify the disruption of the Araucaria Forest system under climate change scenarios, we analyzed the adjacency matrices of ecosystem services (i.e., the original and those with penalization due to climate change, following Bogoni et al. 2020a) via ecological networks (Boccaletti et al. 2006). For each network (i.e., original and under climate changes scenarios), we obtained the following: (1) interviewed degree (Id), (2) ecosystem services degree (ESd), (3) connectance (C), (4) nestedness (N), and (5) modularity (M). The average degree (i.e., $\bar{X}$Id and $\bar{X}$ESd) describes the average number of interactions per interviewee and the putative ecosystem services in the network (Boccaletti et al. 2006). Connectance (C) represents the proportion of interactions (i.e., interviewed opinion vs. ES) observed in relation to the total possible interactions (Boccaletti et al. 2006). Modularity (M) quantifies the tendency of the nodes (interviewed–ESs) to form groups of vertices more connected to each other than to the other components of the network (Boccaletti et al. 2006). Nestedness (N) indicates a hierarchical pattern of interviewed-ES interactions, in which the less connected interviewed-ES interactions form a subset of the most connected interactions, representing a structural fitting (Almeida-Neto et al. 2008). We compared the metrics between the original adjacency matrix and climate change regimes, where any numerical change of the metrics suggests a loss of robustness or stability of the network of services provided by the Araucaria Forest system.

3. Results

3.1 The potential loss of Araucaria Forest due to climate change

According to the four peer-reviewed studies showing the impacts of the potential loss of Araucaria Forest due to climate change, we identified that by 2070, climate change will shrink the Araucaria Forest system area up to 68.37%. The RCP 8.5, which leans towards the most pessimistic climate previsions, indicates a suitable area loss of up to 80%, while the RCP 4.5, an optimistic climate projection, indicates a potential suitable area loss of up to 56% compared to the current Araucaria Forest extent (Table 1). Furthermore, no more than 10% of the projected distribution of the Araucaria Forest (i.e., currently or in the future) will be encompassed by existing protected areas according to these studies, which only considered Brazilian fully protected and sustainable use protected areas (*Proteção Integral* and *Áreas de Uso Sustentável*, respectively). These climatically suitable areas might also be encompassed by private protected areas, such as legal reserves and permanent preservation areas (*Reserva Legal* and *Área de Preservação Permanente*), besides Indigenous Territories. Finally, it is expected that the remaining forest will be restrained to more elevated areas.

3.2 Traditional ecological knowledge about *pinhão* and climate change

We recorded 23 local *pinhão* ethnovarieties based on 320 citations from all participants throughout southern and southeastern Brazil. These ethnovarieties were described by local people (i.e., smallholders and/or *pinhão* extractors) based on *pinhão* ripening periods by female araucarias. The cluster dendrogram showed that among the 23 ethnovarieties described by interviewees, seven properly represented the differences or similarities according to the descriptions (i.e., color, shape, ripening period, size, taste), especially the following: (i) '*Macaco*', (ii) '*25 de Março*', (iii) '*São José*', (iv) '*Cajuvá*', (v) '*Comum*', (vi) '*Do Cedo*', (vii) and '*Do Tarde*' (Fig. S1). The most cited *pinhão* ethnovarieties were the following: (i) '*Macaco*' (N = 81 citations), (ii) '*Cajuvá*' (N = 80 citations), (iii) '*Comum*' (N = 48 citations), (iv) '*Do Cedo*' (N = 31 citations), and (v) '*25 de Março*' (N = 16 citations). Participants cited, on average, three ethnovarieties (52.5%) and another 25% described four ethnovarieties. The main ethnovarieties described by the participants were said to develop at different times of the year, indicating *pinhão* production throughout the year, especially from March to December (Fig. 2). The ethnovarieties '*Do cedo*' and '*Cajuvá*' were classified as the most abundant, which confirms that *pinhão* peak production occurs from March to July. '*Macaco*' is the rarest ethnovariety according to 67% of interviewees (N = 65). We also recorded some new *pinhão* ethnovarieties in the study area. Usually, the '*Cajuvá*', '*Macaco*', '*Do Cedo*', and '*Do Tarde*' ethnovarieties are commonly described in the states of Paraná, Santa Catarina, and Rio Grande do Sul. However, in the municipality of Cunha (Mantiqueira Hills region) the most described ethnovarieties were '*Caiano*' and '*Roxo*'.

Interviewees were also asked to describe how they perceive the effects of climate change in the Araucaria Forest. Only eight interviewees did not answer this question, while 91.75% (n = 89) believe that climate change will somehow impact the ecosystem. Increasing temperatures, whiter winters, and less frost were the main aspects described by 74.15% (N = 66) of the interviewees as the consequences of climate change. Climate unpredictability, such as anomalous or unstable winter and summer seasons, was also described as one of the main changes perceived throughout the landscape (46% or N = 41). We also asked whether the araucaria tree would be affected by climate change. Among the 89 interviewees, 36 (40.4%) did not indicate that araucaria will be affected by climate change, while for those who suggested climate change would influence araucaria (53 interviewees), 50.1% (N = 27) believe the species will move to colder areas and 35.8% (N = 19) stated the species will move to higher elevations (see Fig. 4 for a complete description about the perception of smallholders and *pinhão* extractors).

3.3 Socioeconomic benefits of *pinhão* extractivism

Pinhão extractivism and trade have been an alternative economic resource for smallholder families for at least 3.5 generations, and 65% of the 97 interviewees declared that *pinhão* trade contributes R $1000 to R $2500 to their monthly income; this was 1 to 2.3 times the Brazilian minimum wage in 2018, or US $253.8 to US $633.9 in 2019 (i.e., US $1 = R $3.94), according to the World Bank Indicator (https://data.worldbank.org/indicator/PA.NUS.FCRF?locations=BR). For 30% of the interviewees, the *pinhão* trade is their main annual income source. Typical crops, such as *yerba-mate*, tobacco, corn and beans, are alternative income resources. *Pinhão* extraction is mainly done by men (95%, N = 92). Women usually contribute by gathering *pinhão* under araucaria trees. Family groups might collect up to 10,000 kg of *pinhão* per year (11.5% or 11 people). Another 50% (N = 46) commonly collects from 1,000 to 10,000 kg per year. The economic value of the *pinhão* trade increased from 2010 to 2019 (Table 02). The three southern Brazilian states, Paraná, Santa Catarina and Rio Grande do Sul, extract, on average, 7,736,000 kg of *pinhão* per year. This amount contributes to US $3,803,245, on average, per year in the South Region of Brazil (Table 03). In southeastern Brazil, the states of São Paulo and Minas Gerais also benefit from the *pinhão* trade. Minas Gerais has been increasing *pinhão* extractivism, collecting 1,126,000 kg per year, totaling US $855,983.77 per year (Table 3). For São Paulo State, both the amount collected and the monetary value of *pinhão* in the market have increased (Fig. 3).

Table 2. The amount of *pinhão* harvested per year (kg * 1000) in the Brazilian states registered at CEASAS (State Supply Centers).

Pinhão harvest between 2010–2019 (kg x 10³)										
Brazilian States	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
Minas Gerais	276	164	87	323	1162	1213	1090	1288	1535	2108
São Paulo	355	6	6	6	6	6	6	6	6	5
Paraná	2536	4581	5932	3924	3582	3220	3183	3596	3373	3290
Santa Catarina	1799	2476	2790	3213	3147	3192	2663	3456	3621	3120
Rio Grande do Sul	749	806	823	828	881	762	805	947	1025	819
Source: IBGE - Produção da Extração Vegetal e da Silvicultura										

Table 3
The economic value of *pinhão* harvested per year (US$ * 1000) in the Brazilian states registered at CEASAS (State Supply Centers).

Pinhão harvest between 2010–2019 (US$ x 10³)										
Brazilian States	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
Minas Gerais	137	73	20	65	471	517	457	505	622	955
São Paulo	297	2	4	4	4	4	5	5	6	6
Paraná	831	1666	2259	1790	1881	2034	2097	2524	2505	2598
Santa Catarina	771	707	983	1449	1943	2216	2335	1870	2231	2729
Rio Grande do Sul	278	333	393	482	606	606	793	922	957	897
Source: IBGE - Produção da Extração Vegetal e da Silvicultura										

3.4 Ecosystem services perceptions by TEK holders

The TEK holders' perceptions were grouped into 19 ecosystem services assigned to the following: (i) provision (resource for human groups, seed predation and dispersion, genetic resource, phytodemographic dynamic); (ii) regulation (climate regulation, disease control, insect control, biological control, natural disaster control, pollination); (iii) cultural (ecotourism, ethnocultural identity, aesthetic, education); and (iv) support (soil formation, oxygen and nutrient cycling, primary production). TEK holders identified one to 14 ecosystem services (mean 3.94) among the 4 assigned services. The assigned services (i.e., provision, regulation, cultural, and support) were identified almost three times (mean 2.84) per TEK holder. The most perceived ecosystem services were the following: (i) resource for human groups, due to *pinhão* use and trade (N = 96); (ii) ethnocultural identity, because of the ethnovariety knowledge and description (N = 76); (iii) climate regulation, due to their perception of araucaria phenology and potential climate change impacts on the ecosystem (N = 75); (iv) phytodemographic dynamics, as a consequence of araucaria occurring in the landscape and its climatic niche (N = 40); and (v) aesthetic, given the interaction of people with the environment based on human perceptions and judgments (N = 24) (see Fig. 5 for a complete description of all perceived ecosystem services).

The metrics evaluating the ecosystem services scenarios in the present and future projections (2050 and 2070) indicated a decrease in every metric evaluated (Fig. 5). The average services degree according to our 97 interviews originally was $\bar{X}ESd_{Original}$ = 22.95. Assuming a random loss of 50% of the ecosystem services by 2050, the potential services might be reduced to $\bar{X}ESd_{2050}$ = 11.84. Under a potential loss of 70% of the ecosystem services perceived by TEK holders, ecosystem services might be $\bar{X}ESd_{2070}$ = 6.95. The other network metrics (i.e., connectance, modularity, and nestedness) also reflect these projected losses. Connectance was originally $C_{Original}$ = 0.24 and decreased to C_{2050} = 0.12 (50.0% reduction) and C_{2070} = 0.07 (70.8% reduction). Modularity increased towards the future: $M_{Original}$ = 0.24; M_{2050} = 0.35; and M_{2070} = 0.48. Finally, nestedness of our ecosystem services network might decrease as well: $N_{Original}$ = 72.5 in the present; N_{2050} = 32.6 in 2050 (55% reduction); and N_{2070} = 12.8 in 2070 (82.5% reduction; Fig. 5).

4. Discussion

4.1 The potential loss of Araucaria Forest due to climate change and its impacts from a holistic perspective

Using the most recent studies about the effects of climate change on *A. angustifolia* and, consequently, to the entire SES of the Araucaria Forest in Brazil, we showed the main socio-economic, ethnoecological, and ecological aspects that might be at risk during medium- (2050) and long-term (2070) climate change. We found evidence using an ethnoecological approach that smallholders and *pinhão* extractors, who use, manage, differentiate *pinhão* ethnovarieties and/or sell *pinhão*, provide several ecosystem services, socioeconomic benefits, and potential resilience to disturbances, such as climate change. By undermining this vulnerable group to global change, the entire SES might be doomed. Furthermore, it is paramount to quantitatively understand the effects of biodiversity loss on human well-being under the science of ecosystem services (Bogoni et al. 2020b), and we provide a valuable contribution using an ecological (Bogoni et al. 2020a) and 'cultural keystone' (sensu Garibaldi and Turner 2004) species as the main proxy in the Araucaria Forest SES.

4.2 Araucaria ethnovarieties as an ecological keystone resource

Besides its umbrella and nurse effects, which structure, increase sapling richness, and promote plant species diversity, regeneration, and development under its canopy (Reis et al. 2018; Sühs et al. 2018), *A. angustifolia* is of pivotal importance in maintaining the fauna community and diversity. Due to its available resource (*pinhão*), araucaria provides local fauna the following: (i) low temporal redundancy (i.e., few other plant resources are available when *pinhão* is available); (ii) low consumer specificity (i.e., *pinhão* is usually consumed by different species); (iii) high resource reliability (i.e., the staggering availability of *pinhão* throughout the year); and (iv) resource abundance (i.e., high production of *pinhão*). Consequently, araucaria structures the associated consumers spatiotemporally (Bogoni et al. 2020a), such as mammals (*Dasyprocta azarae*, *Delomys dorsalis*, *Oligoryzomys nigripes*, *Procyon cancrivorus*, *Tayassu pecari*) and birds, for example, *Amazona vinaceae*, *A. pretrei*, *Cyanocorax caeruleus*, and *C. chrysops* (Iob and Vieira 2008; Montagna et al. 2019).

By identifying the *pinhão* ethnovarieties and their peak production during the year, which is mainly between March and December, we also suggest that both keystone plant resource aspects, (i) high resource reliability and (ii) resource abundance characteristics, might be a consequence of the historical domestication process of this species by human groups. '*Macaco*', on one hand, is usually described as the "rarest" and "smallest" *pinhão* ethnovariety, but it occurs throughout the year (Adan et al. 2016; Tagliari and Peroni 2018). The most abundant variety ('*Cajuvá*'), on the other hand, is commonly described as the "*biggest*" or "*tastier*" *pinhão* (Adan et al. 2016; Tagliari and Peroni 2018). We believe that both the reproductive phenology and ethnovariety characteristics of araucaria are consequences of the domestication process and the use of araucaria resources since the time of pre-colonial Amerindians (Cruz et al. 2020), benefiting and structuring both the fauna and flora in the Araucaria Forest system.

Forest management in the Araucaria Forest system region for the past 1400 years expanded this forest beyond its natural extent in areas with an elevated demography (Robinson et al. 2018). We advocate that the current use and knowledge of araucaria ethnovarieties still shape and maintain the productivity and preservation of this ecosystem from a landscape domestication perspective (Reis et al. 2018), where management practices, the species demographic structure, and its genetic diversity reinforce this concept (Reis et al. 2018). Assuming that climate change might drastically reduce the distribution of araucaria by 2070 (Castro et al. 2019; Wilson et al. 2019; Marchioro et al. 2020, Tagliari et al. 2021b), this effect might ruin critical ecological interactions, as well as collapse the actual human-plant interaction.

4.3 Socioeconomic impact and ecosystem services declines

The actual human-plant interaction results in economic profits not only to local smallholders and *pinhão* extractors but to an entire network until the final consumers (Vieira-da-Silva and Miguel 2017). The SIDRA historical series of *pinhão* trade and consumption (see Tables 1; 2) only accounts for the *pinhão* traded at Brazilian CEASAS (*State Supply Centers*). However, there is an "informal" market for *pinhão* that does not involve CEASAS and is not accounted for in the historical series. This informal market is mostly linked to local landowners and people that sell *pinhão* along Brazilian state highways, which supply markets in smaller cities, mainly in the highlands of southern Brazil and specific regions in the Mantiqueira hills in the southeastern portion of the country (Adan et al. 2016; Tagliari and Peroni 2018; Quinteiro et al. 2019). Despite the vertiginous increase in the value of *pinhão* per year in Brazil (Fig. 3b), which indicates an appreciation of *pinhão* consumption, the amount collected per year (Fig. 3a) reveals that *pinhão* harvesting might be already reaching its limit. The uncontrolled *pinhão* harvesting is made by smallholders and *pinhão* extractors exclusively via extractivism. However, uncontrolled *pinhão* harvesting might be dangerous because there is a critical intensity threshold between 60 and 85% (Fichino et al. 2017). By exceeding this threshold, uncontrolled *pinhão* harvesting might prevent, in both the short- and long-term, araucaria regeneration, as well as limit and reduce ecosystem services, such as provision (*pinhão* provisioning), support (primary production), and regulation (carbon sequestration) (Fichino et al. 2017).

Table 2
The amount of *pinhão* harvested per year (kg * 1000) in the Brazilian states registered at CEASAS (State Supply Centers).

Pinhão harvest between 2010–2019 (kg x 10³)										
Brazilian States	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
Minas Gerais	276	164	87	323	1162	1213	1090	1288	1535	2108
São Paulo	355	6	6	6	6	6	6	6	6	5
Paraná	2536	4581	5932	3924	3582	3220	3183	3596	3373	3290
Santa Catarina	1799	2476	2790	3213	3147	3192	2663	3456	3621	3120
Rio Grande do Sul	749	806	823	828	881	762	805	947	1025	819
Source: IBGE - Produção da Extração Vegetal e da Silvicultura										

The very few regulations for *pinhão* harvesting are limited to when the extraction season begins. This is usually on 1 April in the states of Paraná and Santa Catarina or 15 April in the state of Rio Grande do Sul; we found no information for the states of São Paulo and Minas Gerais. However, the majority of extractors usually gather and trade *pinhão* for financial subsistence and food security, and not to guarantee the conservation of the species, ecosystem maintenance, or sustainable harvesting (Adan et al. 2016; Tagliari and Peroni 2018; Quinteiro et al. 2019; Tagliari et al. 2021a). The lack of environmental incentives, especially via payment for ecosystem services (Tagliari et al. 2019), promote, especially for landowners, antagonistic conservation practices, such as araucaria seedling suppression (Tagliari and Peroni 2018; Schneider et al. 2018; Quinteiro et al. 2019). It is widely documented that TEK holders claim to need a public policy that values their interactions and the indirect consequences of preserving araucaria (Adan et al. 2016; Tagliari and Peroni 2018; Quinteiro et al. 2019) since this socioeconomic and ecological interaction promotes gene flow (Zechini et al. 2018), genetic diversity (Montagna et al. 2019), intraspecific diversity for araucaria populations (Mello and Peroni 2015; Adan et al. 2016; Reis et al. 2018; Quinteiro et al. 2019), maintenance of productive forest remnants via "conservation-by-use" (Reis et al. 2018), and the maintenance or even the expansion of the entire socio-ecological system via positive feedbacks (Tagliari et al. 2021a).

Due to climate change, however, TEK holders might be even more vulnerable because of their dependence on climatic conditions (Holland et al. 2017). In the Araucaria Forest system, TEK holders usually live under food insecurity, poverty and precarious conditions, reinforcing their socioeconomic vulnerability. The imminent impacts of climate change within the Araucaria Forest, especially on *A. angustifolia* (Castro et al. 2019; Wilson et al. 2019; Marchioro et al. 2020), and the potential cascading effect to the entire socio-ecological system will impact one of the major contributors to the maintenance of this SES. We might witness a combination of threats in both the short- and long-term along the Araucaria Forest: unsustainable harvesting, precarious socioeconomic conditions of TEK holders, and the imminent impact of climate change.

Under climate change, we revealed that the ES provided by the Araucaria Forest will undermine and thus compromise human well-being. For instance, the presumed ecosystem services degree could decline by 69.7% by 2070. The ecological network of ES perceived by the small landowners based on their TEK could also be threatened due to climate change decreasing all the metrics, such as connectance and nestedness (65% loss on average). The increase in modularity can indicate dense connections within the nodes in every cluster in 2070 but with a sparse connection between different nodes (i.e., the perception of ES could be shared by subgroups of people, but not shared by the group as a whole). Empirical evidence indicates a similar pattern in decline of ES and network rearrangements due to mammal defaunation scenarios (Bogoni et al. 2020b). Given that the ecological network is a tool to understand, depict and predict ecosystem functioning, species interactions and ecological functions (Boccaletti et al. 2006), the Araucaria Forest SES may be disrupted due to climate change.

4.4 Food security and sociocultural interconnection with the Araucaria Forest system

Climate change projections and the potential reduction of the distribution of araucaria is a major concern for local communities and their food security. The *pinhão* from araucaria is a nutrient-rich food resource that contains several minerals (e.g., potassium, phosphorus, and manganese; Barbosa et al. 2019). Since it is a typical regional resource, which guarantees both economic and dietary security to local human groups, strengthening the traditional use and management of local food resources might also preserve local keystone species (Tagliari et al. 2021b). Also, this would support the maintenance and aesthetic connection of the cultures of peoples, and how human groups perceive and incorporate a sense of belonging with the surrounding environment (Tam and Chan, 2007). Consequently, since climate change might disrupt the araucaria socio-ecological system, there is a necessity to implement strategies to safeguard and preserve this cultural ecosystem (Tam and Chan, 2017).

5. Conclusion

5.1 Araucaria Forest contributions to people and the contribution of people to the Araucaria Forest: the pathway to promote resilience to climate change

Several aspects must be considered to avoid the imminent impact of climate change on the Araucaria Forest system. The first is the cornerstone of conservation: protected areas (Rodrigues and Cazalis 2020). For the Araucaria Forest, only 10.3% of the more than 1,118,000 km² is protected (Indigenous Territories cover only 0.72% or 8,050 km²); 25% is classified as strict protected areas and 75% as sustainable use areas (Pacheco et al. 2018). Within the sustainable use areas, two categories could potentially benefit TEK holders of the Araucaria Forest: sustainable development reserves (RDS) and extractive reserves (RESEX). However, of the 75% classified as sustainable use areas, only 1.07% is classified as RDS or RESEX, while 72% is classified as environmental protection areas (Pacheco et al. 2018), which do not benefit local peoples. This might be a consequence of legal reserves (private protected areas), which contain another one-third of the remaining remnants of the Atlantic Forest on private properties, such as smallholder properties. Concerning *A. angustifolia*, only 5 to 10% of its predicted suitable areas in the future (i.e., which are expected to decrease by ≌70% by 2070) will be encompassed by the existing protection network (Castro et al. 2019; Marchioro et al. 2020). These suitable areas will be in more elevated, moister, colder areas (Castro et al. 2019; Wilson et al. 2019; Bergamin et al. 2019; Marchioro et al. 2020), as TEK holders also described in this study (Fig. 04). Consequently, the first conservation priorities as a response to climate change are to identify these potential areas and create new protected areas, as well as create RESEX and RDS sustainable use areas.

The second major aspect is targeting the main actors in this socio-ecological system: TEK holders. Different potential strategies must be implemented to value this human-plant interaction under the payment for ecosystem services framework: (i) conservation of forest stands beyond the minimum legally required; (ii) valuation of the *pinhão* supply chain; (iii) maintenance of *pinhão* ethnovarieties; (iv) mensuration of the ecosystem services provided by remnant areas; (v) restoration of degraded areas; and (vi) food security for vulnerable social groups (see Tagliari et al. 2019 for an evaluation of different payment for ecosystem services programs in southern Brazil). Also, recent studies shed light on the possibility of sustainable timber exploitation as a strategy to engage local people (Orellana and Vanclay 2018; Montagna et al. 2019). Hence, by valuing these actors, araucaria intraspecific and functional diversity are boosted and, consequently, promote resilience and adaptive capacity to climate change, besides creating positive feedback between TEK holders and the entire socio-ecological system (Elmqvist et al. 2003; Holland et al. 2017; Tagliari et al. 2021a). Further, by preserving araucaria remnants via TEK holders we find a win-win strategy because there is the possibility of engaging more local groups in environmental governance and reducing actions that degrade the surrounding environment thanks to restrictive measures that usually exclude local groups (Tam and Chan 2017; Orellana and Vanclay 2018; Zechini et al. 2018; Tagliari et al. 2021a). Notwithstanding, the perception of ecosystem services by TEK holders indicates profound knowledge and a commitment to the Araucaria Forest, providing ecosystem services, such as regulation, provision, and cultural services.

We do not expect to treat TEK holders as a new panacea to fight against climate change. However, especially for socio-ecological systems worldwide, there is a necessity to implement holistic, integrative, and non-mutually exclusive conservation measures using top-down (such as restrictive legislation or strict use protected areas) to bottom-up (such as collaborative management initiatives with traditional human groups, payment for ecosystem services, or sustainable use protected areas) strategies. By using this integrative approach, we might reinforce resilience and adaptive capacity to anthropic disturbances in the Araucaria Forest. Otherwise, if we do not seek an integrative response, this valuable socio-ecological system might be disrupted by climate change.

Declarations

ACKNOWLEDGEMENTS

This manuscript is the result of 8 years of listening to, learning from, and discussing with local smallholders and *pinhão* extractors in southern and southeastern Brazil. We thank them. We hope our research helps stakeholders and politicians recognize this vulnerable traditional group as a cultural heritage in Brazil. The authors thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES/Brazil; Finance Code 001) for the Ph.D. scholarships given to MMT, JAB, GDB, and APC. JAB is supported by the São Paulo Research Foundation (FAPESP) (postdoctoral fellowship grants 2018-05970-1 and 2019-11901-5). NP thanks the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for the productivity scholarship (Process 310443/2015-6).

Funding

The authors thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES/Brazil; Finance Code 001) for the Ph.D. scholarships given to MMT, JAB, GDB, and APC. JAB is supported by the São Paulo Research Foundation (FAPESP) postdoctoral fellowship grants 2018-05970-1 and 2019-11901-5. NP thanks CNPq for the productivity scholarship (process 310443/2015-6).

Competing Interests

The authors declare no competing interests.

Author Contributions

MMT conceived the study. MMT and JAB wrote the original draft of the manuscript and conceived the main statistical analysis. MMT, JAB, GDB, APC, and NP contributed equally to the main aspects of the research: literature review, statistical analysis, and manuscript revisions. All authors edited and approved the manuscript.

Data Availability

The R code to entirely reproduce the output of this study is available on GitHub: https://github.com/masemuta/disruption_af. Table data are freely available on the SIDRA – IBGEwebsite. Due to ethical aspects, we will provide the ethnoecological data under reasonable request.

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Figures

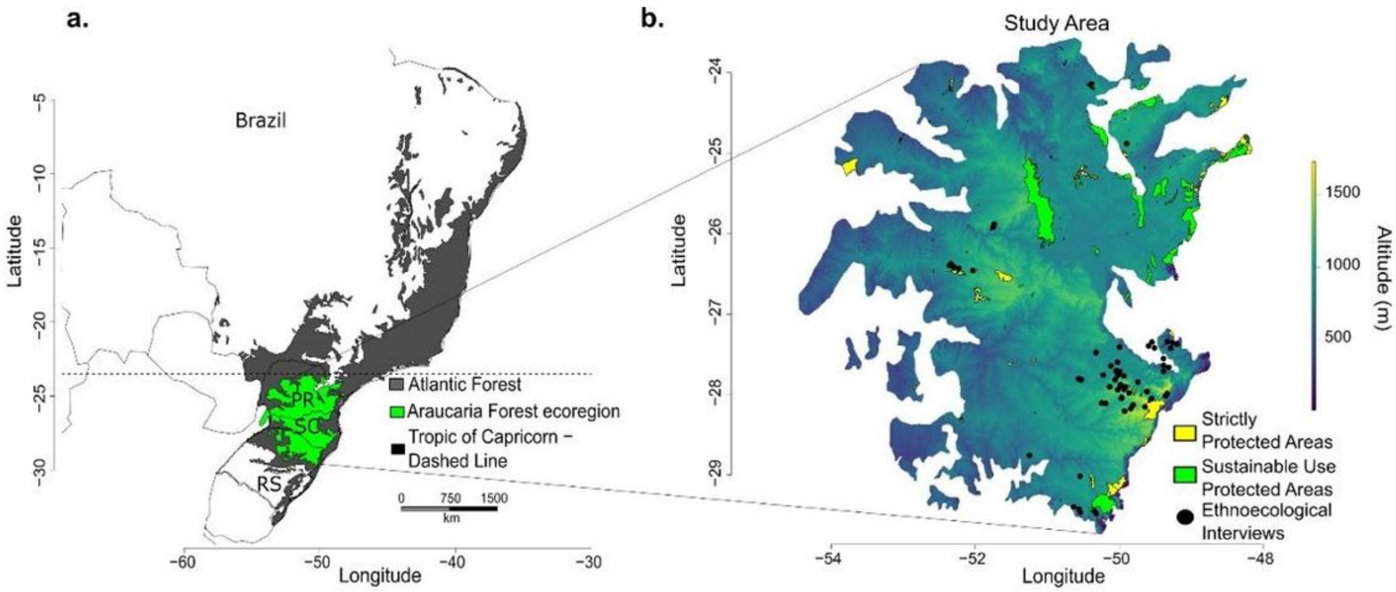

Figure 1

(a) The Atlantic Forest (dark gray), Araucaria Forest ecoregion (green), and the three Brazilian states that mainly encompass the ecoregion: Paraná (PR), Santa Catarina (SC), and Rio Grande do Sul (RS); **(b)** An Araucaria Forest altitude map and the distribution of conservation units: strict (yellow) and sustainable use (green) protected areas; black dots represent the locations of the 97 ethnoecological interviews conducted in this study. Only three interviews occurred in São Paulo State (beyond the Araucaria Forest ecoregion) in municipality of Cunha.

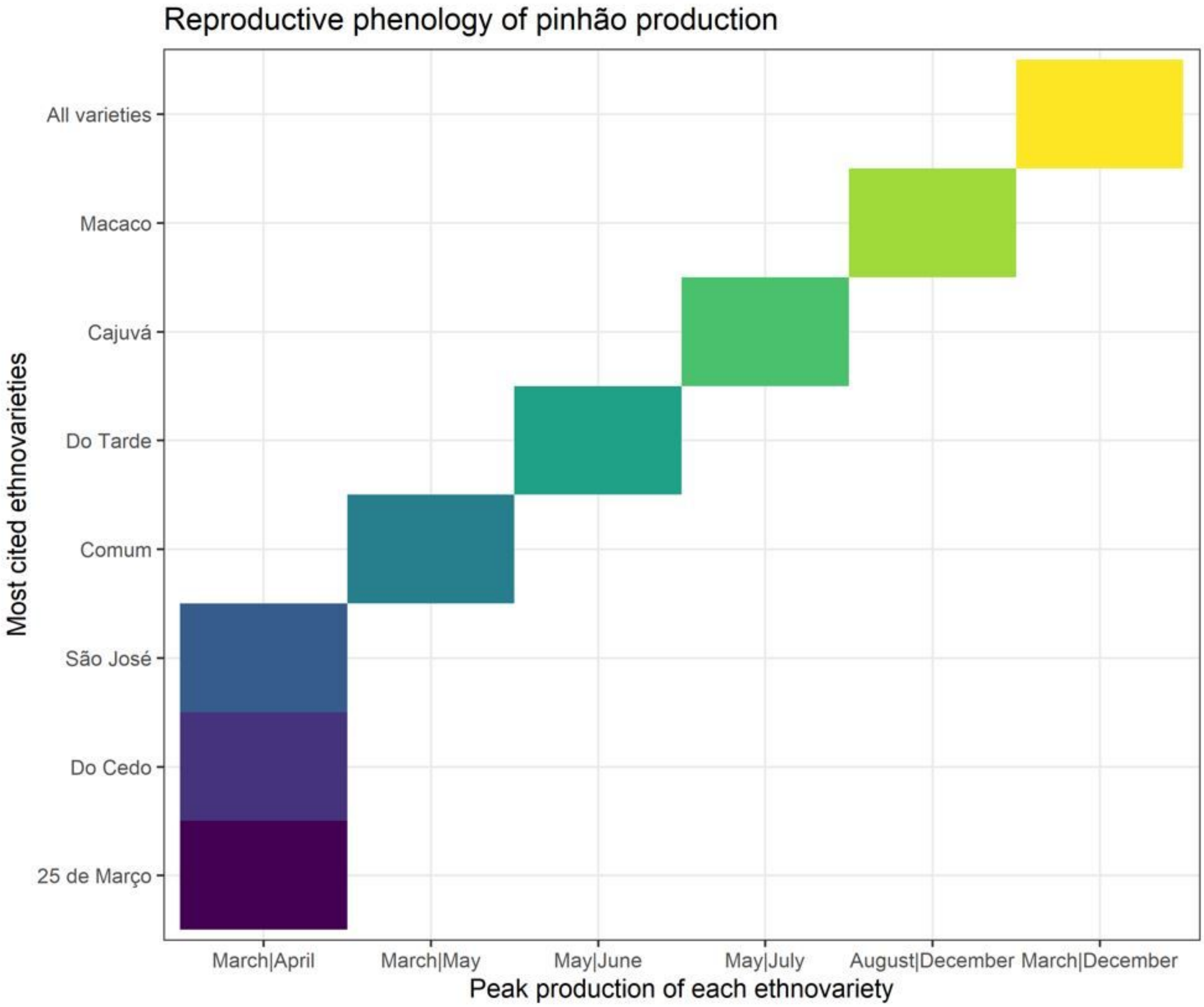

Figure 2

The reproductive phenology of the main *pinhão* ethnovarieties during the year. The peak production of the first ethnovarieties is in March and April (*'25 de Março'*, '*Do Cedo*', '*São José*'). For the two most cited ethnovarieties — "*Cajuvá*" and "*Macaco*" — peak production is from May to July and from August to December. *Pinhão* production for all varieties (yellow square) occurs from March to December.

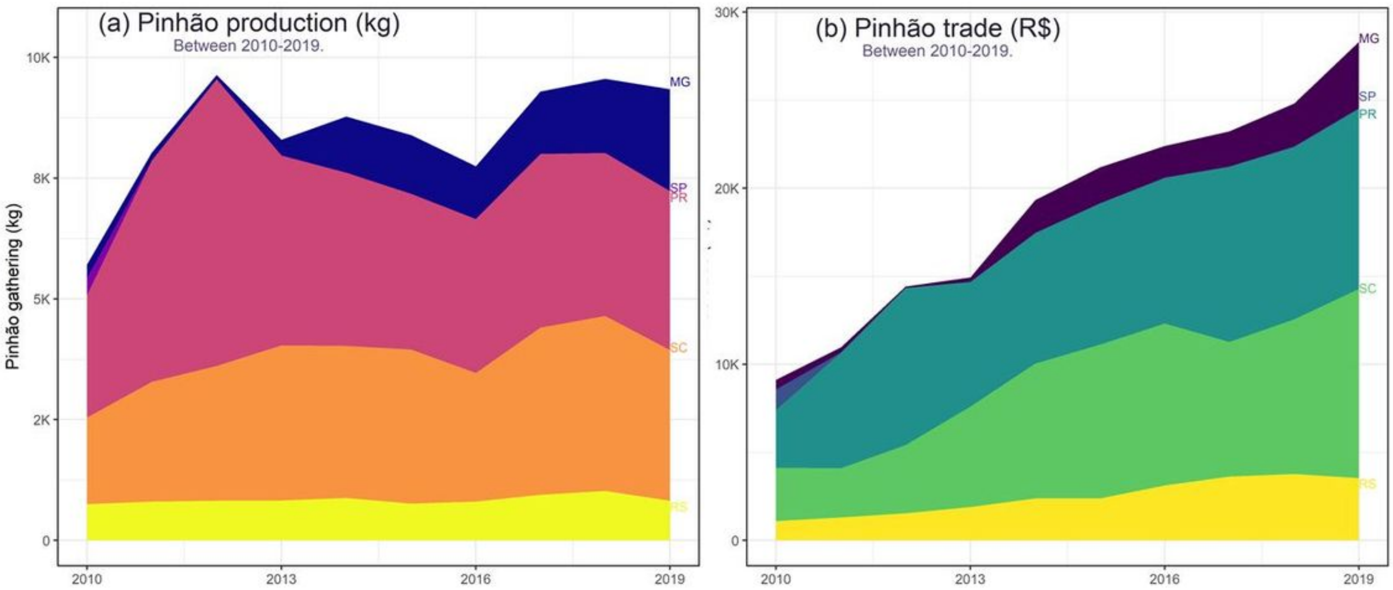

Figure 3

(a) *Pinhão* harvesting (kg) and *pinhão* trade (R$) according to the 2010–2019 time series. *Pinhão* harvesting indicates that all states collecting *pinhão* might have reached their limit in this extraction activity. However, **(b)** the economic value indicates an increase since 2010 and a potential cap for the valuation of *pinhão* trade in the future.

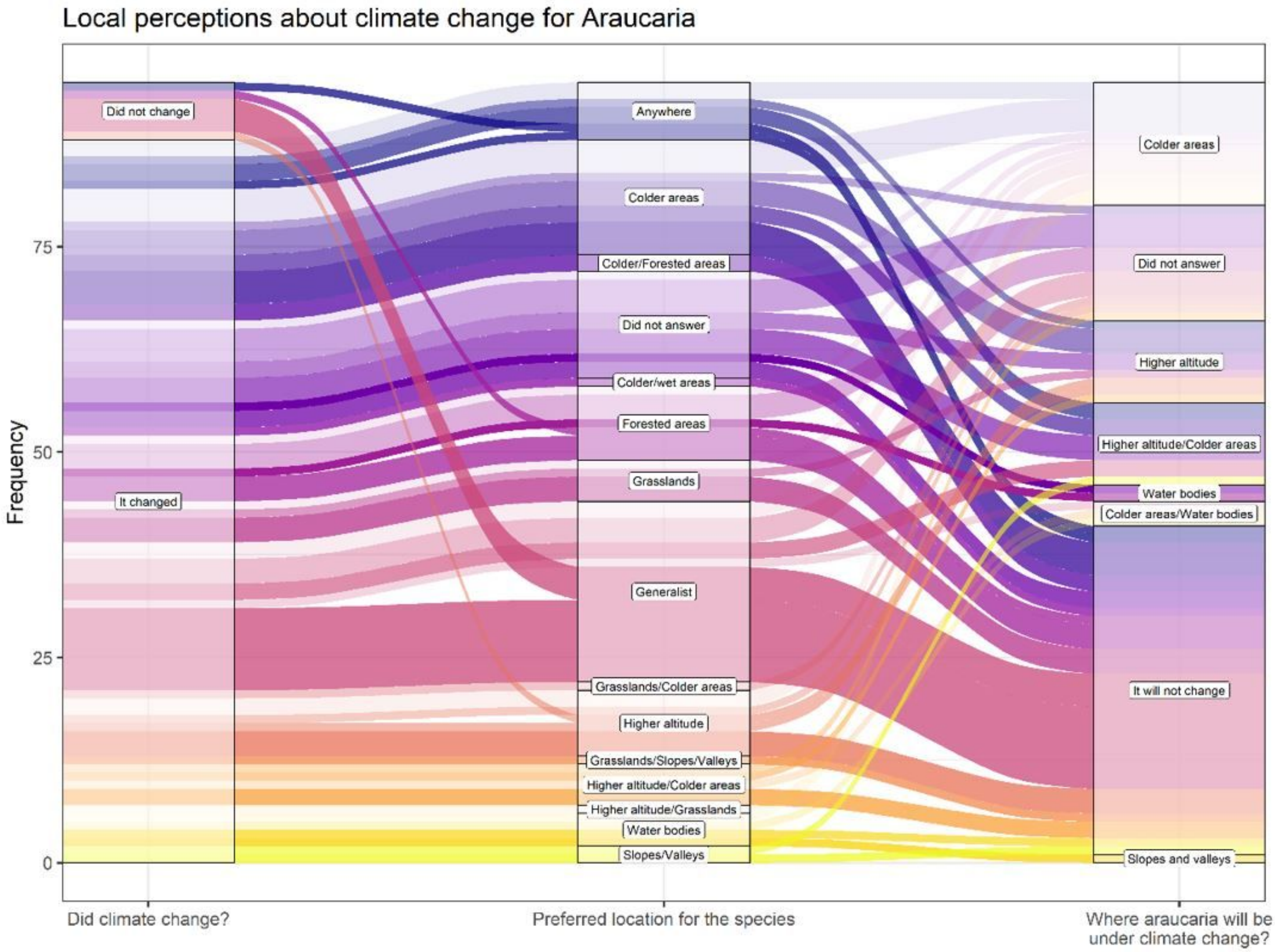

Figure 4

The perceptions of TEK holders about the effect of climate change on araucaria and how this emblematic tree might respond to this disturbance. Semi-structured interviews indicate that TEK holders believe that due to climate change, araucaria might move to more elevated, colder, and moister areas.

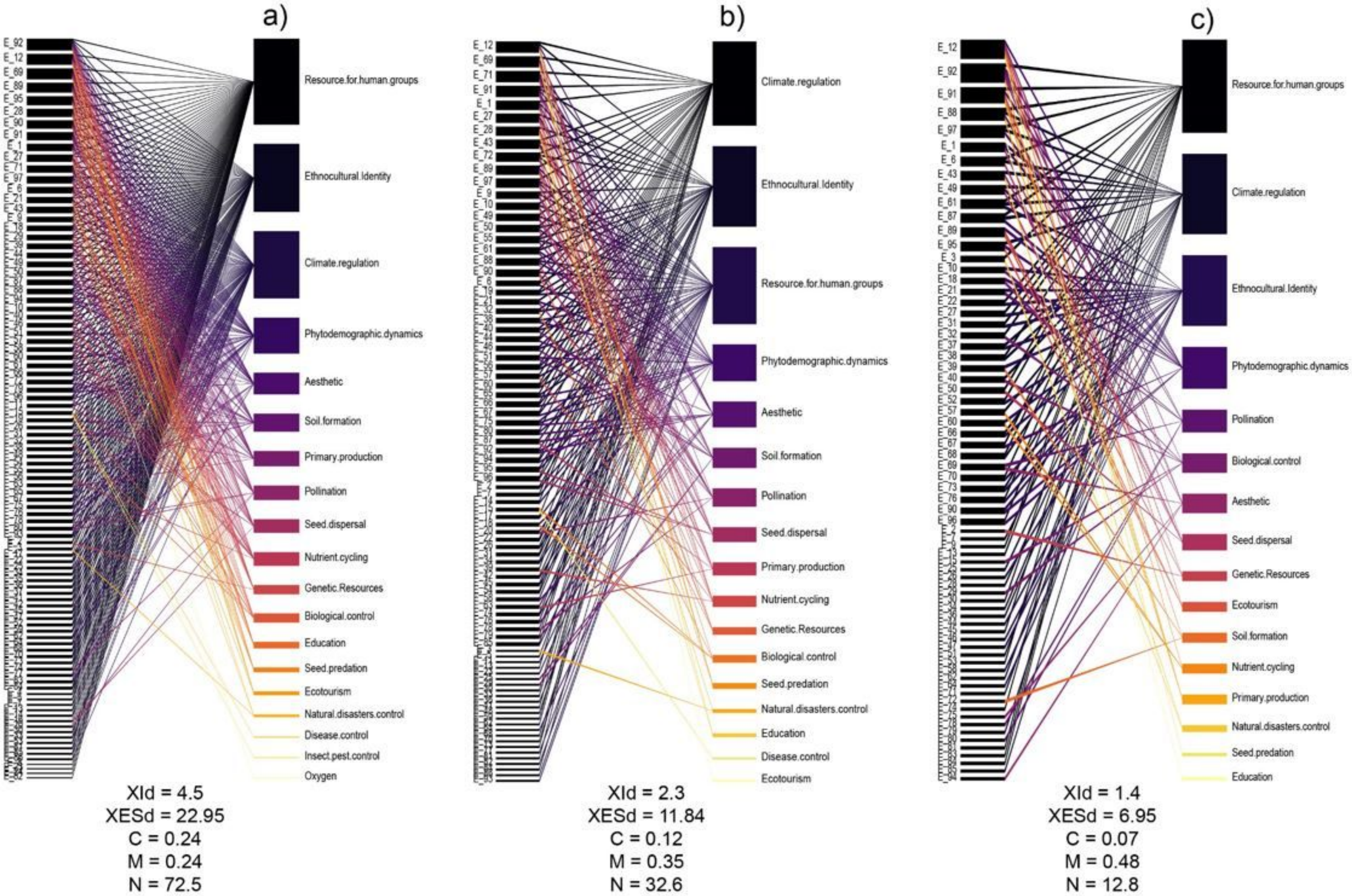

Figure 5

The perceptions of TEK holders (left column) about the ecosystem services (right column) provided by the Araucaria Forest. We represented all answers among the four main ecosystem services that affect the well-being of people: **(i)** provision (resource for human groups, seed predation, seed dispersal, phytodemographic dynamics); **(ii)** regulation (climate regulation, disease control, insect pest control, natural disaster control), **(iii)** cultural (e.g., ethnocultural identity, ecotourism, aesthetics, education); and **(iv)** support (e.g., nutrient cycling, soil formation, primary production, oxygen); following Bogoni et al. (2020a) to select the specific categories for each ecosystem service. To model the potential loss of the perception of ecosystem services due to climate change, we combined the outputs of the most recent peer-reviewed studies that estimated the potential area loss for araucaria by 2050 (i.e., 50% loss of perceived ecosystem services) **(b)** and 2070 (i.e., 70% loss of perceived ecosystem services) **(c)**. Values are represented by interviewed degree (Id), ecosystem services degree (ESd), connectance (C), modularity (M), and nestedness (N).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplementarymaterial16042022.docx