Disrupting a socioecological system: how Traditional Ecological Knowledge could be the key to preserve Araucaria Forest in Brazil under climate change?

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Abstract

Socioecological systems (SES) hinge on human groups and ecosystems, promoting interdependence and resilience to environmental disturbances. Climate change effects propagate from organism to biomes, likely influencing SES. In southern Brazil, Araucaria Forest is a typical SES due to the historical interaction between humans and biodiversity. We thus aimed to evaluate empirically and theoretically how climate change could disrupt this system by interviewing 97 smallholders and assessing their Traditional Ecological Knowledge (TEK). We evaluated and measured: (i) socioeconomic impact of araucaria's nut-like seed (*pinhão*) trade; (ii) ethnoecological knowledge about climate change; and (iii) generated an ecosystem services network. We projected these empiric 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 socioecological system. We found evidence that to avoid the disruption of the Araucaria Forests is paramount to value TEK holders, safeguard the historical socioecological interaction, and promote non-mutually exclusive measures in an integrative response to maintain the Araucaria Forests resilient to future disturbances.

Introduction

Climate change effects have been widely described throughout all ecosystems (Malhi et al. 2020), from organism to biome levels (Parmesan 2006), affecting from organism's genetics (e.g. allelic diversity) to biomes integrity, such as the ecological resilience to disturbances (Bellard et al. 2012). These threats also impinge on Socio-Ecological Systems (hereafter SES), which consists in 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 the interaction 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 to hold the Traditional Ecological Knowledge (hereafter TEK): a long-term experience, based on observation, use, and management of natural resources, which offers a basis for ecosystems' adaptation and resilience to environmental disturbances, such as climate change (Ladio 2017).

The ecosystems under continuing interaction between plants and peoples are examples of SES. For instance, enduring human-plant interactions in the Neotropics contributed to enhancing plant domestication and food security across both the Amazon (Levis et al. 2018) and Araucaria Forest in southern Brazil (Cruz et al. 2020). Precisely, the Araucaria Forest, also known as Araucaria Mixed Forest, is an emblematic SES of the subtropical Atlantic Forest region (Tagliari et al. 2021a). The main plant species of this ecosystem is the candelabra-aspect tree *Araucaria angustifolia* (Bertol.) Kuntze, popularly known as araucaria, a '*Critically Endangered'* species — according to the International Union of Conservation of Nature — which was almost depleted owing to extensive and illegal logging from early to late 20th century (Thomas 2013). The species has an ecological keystone role in the ecosystem's functioning owing to its nut-like seed, known as *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 the ancient connection with Indigenous peoples and local communities (Reis et al., 2014; Robinson et al., 2018), who still use and manage *pinhão* (Adan et al. 2016; Quinteiro et al. 2019). Forest management strategies by human groups since the last 1400 years expanded the Araucaria Forest beyond its natural boundaries, with landscape modifications visible in present days (Robinson et al. 2018; Cruz et al. 2020). Currently, the traditional management systems by local smallholders: (i) maintain forest fragments productive (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 *pinhões* ethnovarieties identification thanks to TEK holders (Adan et al. 2016; Tagliari and Peroni 2018; Quinteiro et al. 2019). These traditional systems under TEK holders also boost positive feedbacks which might expand Araucaria Forest (Tagliari et al. 2021a). Consequently, araucaria is also classified as a "Cultural Keystone Species" (Garibaldi and Turner 2004), once it portrays a cultural and socio-ecological role in southern Brazil (Reis et al. 2014; Adan et al. 2016; Quinteiro et al. 2019). Further, it brings solid arguments that the entire ecosystem behaves as a socioecological 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 dampening araucaria conservation and the SES resilience. To halt biodiversity losses the creation of protected areas is a cornerstone strategy (Geldmann et al. 2013). The Araucaria Forest remnants, although, are still poorly encompassed by the existing protected area network, as recent studies showed that less than 10% of the species' projected distribution falls within an existing protected area rather in the present or under 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 late 19th century, Araucaria Forest's natural extent covered an estimated area of 200 000 km² spanning over Brazil, Argentina, and Paraguay (Nodari 2016). Due to deforestation no more than 30% of native remnants remain preserved (Rezende et al. 2018). Moreover, future climate change predictions indicated losses of climatically suitable areas ranging from 60% to 96.5% compared to the species' current distribution (Castro et al. 2019; Wilson et al. 2019; Marchioro et al. 2020).

Despite these studies showing the species' vulnerability 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 answer this knowledge gap by approaching one of the main actors behind the SES resilience in the Araucaria Forest: the local smallholders. First, because of their TEK leaning on araucaria use and management (Mello and Peroni 2015; Adan et al. 2016; Quinteiro et al. 2019), which promote resilience to climate disturbances and functional diversity (Ladio 2017; Tagliari et al. 2021a). Second, Brazilian Legislation has a specific protected area category within private areas, the "*Reservas Legais*" (Legal

Reserves), a compulsory protected area that hosts almost one-third of all remaining native vegetation of the Atlantic Forest (Metzger et al. 2019). Consequently, TEK holders preserve the majority of araucaria native remnants because, in southern Brazil, 20% of private properties must be retained to native vegetation (Orellana and Vanclay 2018). Third, communities of poor small farmers might be the most vulnerable group due to global environmental changes (Pyhälä et al. 2016).

We thus propose to depict which aspects within the Araucaria Forest SES might be at risk due to climate change, looking at a social, economic, ecologic, ethnoecological, and ecosystem services framework. Further, we aimed to describe how TEK holders could increase Araucaria Forest's resilience to climate change. To achieve this framework, we interviewed 97 smallholders throughout the Araucaria Forest. By assessing their TEK, we aimed to systematically describe why this specific human group might be critical to safeguard the whole Araucaria SES, maintaining its preservation, ecosystem services, araucarias' functional diversity (intraspecific diversity), socio-ecological interactions, and resilience to disturbances, especially contributing to avoid its disruption to climate change.

Materials And Methods

2.1 Study area

The study was conducted through the extent of the Araucaria Forest original distribution where we still find the interaction between human groups with araucaria species (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 is distributed at highlands plateaus along altitudes above 500 m (de Souza et al. 2009), especially in Southern Brazil (states of Paraná, Santa Catarina, and Rio Grande do Sul) and relict occurrence patches in Southeastern Brazil, through the borders of the States of São Paulo, Minas Gerais, and Rio de Janeiro (Quinteiro et al. 2019; Tagliari et al. 2021b).

2.2 Traditional Ecological Knowledge in the Araucaria Forest System in a nutshell

Different human groups interacted with Araucaria Forest through time. Use and management date back to Pre-Columbian times, where paleo-indigenous ethnic groups cultivated *pinhão* (araucaria nut-like seed) for subsistence or religiousness (Reis et al. 2014). Their historical footprint changed the araucaria landscape, where archeological data indicated human-made influence over past forest expansion (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 due 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 the '*conservation-by-use*' (Reis et al. 2018), as well as benefits for human groups, such as (i) economic: *pinhão* trade; (ii) social: cultural identification; (iii) subsistence: food security; and (iv) socioecological: environmental services, ecological resilience, and functional diversity of *pinhões* (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 *pinhões* (ethnovarieties) is well-described in the literature as an example of TEK 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 is this human-plant relationship, 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). We thus used this human group (i.e. local smallholders and *pinhão* extractors) to proceed with the application of a semi-structured questionnaire (Table S1). We used the snowball technique (Bernard 2006) to follow the semi-structured interviews, where participants recommended people directly involved in araucaria management at the end of the interview. We aimed to include indigenous peoples as TEK holders, such as Southern-Jê and Guarani groups, who have shaped forest composition in Southern Brazil (Cruz et al., 2020), however, ethical limitations and legal aspects did not allow us to include them in our study. Our research was approved by the ethics committee of *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 interviewees' gender, age, profession, main crops cultivated, time living in the property, how much *pinhão* trade boost family incomes, and the amount of *pinhão* (in kg) collected in each property. Second, we use the Brazilian System of Automate Recuperation – 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 *pinhão* annual trade (see here https://sidra.ibge.gov.br/tabela/289#resultado).

2.4 Ethnoecological knowledge under 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 *pinhões* ethnovarieties. Leaning on smallholders' TEK we collected evidence of (i) *pinhão* ethnovarieties ripening period, abundance, size, color; (ii) the different *pinhão* ethnovarieties known by each smallholder; (iii) the reproductive phenology and seed production of araucaria trees due to *pinhão* maturation throughout the year; (iv) interviewees perception about the potential impact of climate change over the Araucaria Forest, especially araucaria species. Leaning on these pieces of information we created a framework to describe two aspects of araucaria ethnoecology: (i) the ecosystem's services provided by araucaria use and management, targeting four potential ecosystem services: provision; regulation; cultural; and support (following Bogoni et al. 2020a); (ii) how *pinhão* ethnovarieties use and management confer araucaria functional diversity; socioecological food security; and smallholders well-being 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). According to the Millennium Ecosystem Assessment (2005) the ecosystem services that affect people well-being are described as (i) provision (resource for human groups, seed predation, seed dispersal, phytodemographic dynamics); (ii) regulation (climate regulation, disease control, insect pest control, natural disasters 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 of each ecosystem service. We cross-checked the interviewees' perceptions of ecosystem services with the already published literature to indicate real or potential ecosystem services provided by the AFS.

2.5 Quantifying AFS disruption under climate change

To estimate the potential losses due to climate change over the Araucaria Forest System we selected the latest peer-reviewed studies that have shown the impacts of future climate change over 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 ( ) 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 three studies selected both RCPs 4.5 and 8.5 because it became a common practice of species modelling approaches once they represent an optimistic (RCP 4.5) or a pessimistic (RCP 8.5) CO_2 emission scenario (Riahi et al. 2011; Thomson et al. 2011). We thus counted all six projections of area loss and divided them by the total amount of projections (*n*-projections) to indicate a value that represents the potential area loss of the Araucaria Forest System due to climate change (see Equation 1).

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

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

To quantify the AFS disruption under climate change scenarios, we analyzed the matrices of adjacency of ecosystem services (i.e. the original and the matrices 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: (1) interviewed degree (Id); (2) ecosystem services degree (ESd); (3) connectance (C); (4) nestedness (N); and (5) modularity (M). The average degree (i.e. XId and XESd) describes the average number of interactions by interviewed 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 regarding 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 interactions interviewed-ES, in which the interactions of the less connected interviewed-ES form a subset of the interactions of the most connected, 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 will suggest a loss of robustness or stability of the network of services provided by SES.

Results

3.1 The potential loss of Araucaria Forest due to climate change

According to the three peer-reviewed studies showing the impacts of potential area loss of Araucaria Forest due to climate change, we identified that until 2070, climate change will shrink the Araucaria Forest system area up to 68.37%. The RCP 8.5 — leaning on most pessimistic climate previsions — indicates a suitable area loss up to 80%, while the RCP 4.5 – an optimistic climate projection — pointed out a potential suitable area loss up to 56% compared to the current Araucaria Forest extent (Table 1). Furthermore, no more than 10% of the projected distribution of Araucaria Forest (i.e. currently or in the future) will be encompassed by existing Protected Areas according to these studies, which only considered Brazilian Full Protection and Sustainable Use Protected Areas (*Proteção Integral* and *Áreas de Uso Sustentável*, respectively). These climatically suitable areas might be also 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 at more elevated areas, indicating an upslope niche contracting pattern.

3.2 Traditional Ecological Knowledge about *pinhão* and climate change

According to smallholders, we identified 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) due to *pinhão* ripening periods by female araucarias. The cluster dendrogram showed that among the 23 ethnovarieties described by interviewees, seven represented properly the differences or similarities according to the descriptions (i.e. color, shape, ripening period, size, taste), especially: (i) *Macaco*; (ii) *25 de Março*; (iii) *São José*; (iv) *Cajuvá*; (v) *Comum*; and (vi)

Do Cedo; (vii) *Do Tarde* (Fig. S1). The most-cited *pinhão* ethnovarieties were: (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 different ethnovarieties. The main ethnovarieties described by the participants were said to develop in different moments during the year indicating *pinhão* production throughout the year, especially from March until December (Fig. 2). The ethnovarieties "*Do cedo*" and "*Cajuvá*" were classified as the most abundant, which confirms that *pinhão* peak production occurs between March until July. The *"Macaco*" ethnovariety is the rarest by 67% of interviewees (n = 65). We also identified a completely different identification of *pinhão* according to the regions. Usually, along the Paraná, Santa Catarina and Rio Grande do Sul states, the *"Cajuvá*", "*Macaco*", *"Do Cedo*", and "*Do Tarde*" ethnovarieties are commonly described. However, at *Cunha* municipality (*Mantiqueira* Hills region) the most described ethnovarieties were "*Caiano"* and "*Roxo*".

Interviewees were also demanded to describe how they perceive the effects of climate change in the Araucaria Forest. Only eight interviewees did not answer about the effect of climate change on the Araucaria Forest, while 91.75% (n = 89) believe that somehow climate will impact the ecosystem. The increasing temperatures, whiter winters, and frost reduction were the main aspects described by interviewees as the consequences of climate change for 74.15% (n = 66). The climate unpredictability, such as anomalous or unstable winter and summer seasons, was also described as 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 species will be affected by climate change, while those who suggested the climate change influence over araucaria species (53 interviewees), 50.1% (n = 27) believes that the species will move to colder areas and 35.8% (n = 19) states the species will move to higher elevations (see Fig. 4 for a complete description about smallholders and *pinhão* extractors perception).

3.3 Socioeconomic benefits of *pinhão* extractivism

The *pinhão* extractivism and trade have been an alternative economic resource for smallholders' families for at least 3.5 generations, where 65% of the 97 interviewees declared that *pinhão* trade contributes to their monthly income from R$ 1000 to R$ 2500 (i.e. 1 to 2.3 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. Typical crops such as *yerba-mate*, tobacco, corn, and beans are alternative income resources with *pinhão* extractivism. The *pinhão* extraction is mainly man-made for 95% (n = 92). Women usually contribute to *pinhão* gathering underneath 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 *pinhão* trade has been increasing its economic value from

2010 to2019 (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 Brazil's southern region (Table 03). In southeastern Brazil, São Paulo and Minas Gerais states also benefit from *pinhão* trade. Minas Gerais has been increasing *pinhão* extractivism, collecting 1 126 000 kg per year, totalizing US$ 855 983,77 per year (Table 3). Unless São Paulo state, both the amount collected per year of *pinhão* and the monetary value of this nut-like seed in the market increased (Fig. 3).

3.4 Ecosystem Services perceptions by TEK holders

The TEK holders' perceptions were grouped into 19 ecosystem services assigned to: (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 identify at least one up 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: (i) resource for human-groups, due to *pinhão* use and trade (n = 96); (ii) ethnocultural identity, because of the *ethnovarieties* knowledge and description (n = 76); (iii) climate regulation, thanks to their perception about araucaria phenology and potential climate change impacts on the ecosystem (n = 75); (iv) phytodemographic dynamics, as a consequence of araucaria occurrence in the landscape and its climatic niche (n = 40); (v) and 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 under 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 in 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, originally was $C_{Original}$ = 0.24, decreasing to C_{2050} = 0.12 (50.0% reduction), and to C_{2070} = 0.07 (70.8% reduction). Modularity, increased towards 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% contraction; Fig. 5).

Discussion

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

Using the most recent studies about the effects of climate change over *Araucaria 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 in the medium- (2050) and long-term (2070) climate change. We found under an ethnoecological approach that smallholders and *pinhão* extractors who use, manage, differentiate *pinhão* ethnovarieties, and trade araucaria's *pinhão*, providing 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 (sensu Garibaldi and Turner 2004) keystone species as the main proxy in the SES of the Araucaria Forest.

4.2 Araucaria ethnovarieties as an ecological keystone resource

Besides its umbrella and nurse effect, which structures, increase sapling richness, and promote plant species diversity, regeneration, and development under its canopy in a non-trophic landscape contribution (Reis et al. 2018; Sühs et al. 2018), the araucaria species has pivotal importance in maintaining fauna community and diversity. Owing to its resource availability — *pinhão* — the araucaria provides to local fauna: (i) low temporal redundancy (i.e. few other plant resources available during *pinhão* availability); (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 araucaria nut-like seed). Consequently, araucaria structures the associate consumers spatiotemporally (Bogoni et al. 2020a), such as mammals (*Dasyprocta azarae*, *Delomys dorsalis*, *Oligoryzomys nigripes*, *Procyon cancrivorus*, *Tayassu pecari*) and birds (*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 throughout the year, which is mainly comprised 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 species' domestication process with human-groups. The *pinhão* ethnovariety described as "*Macaco"*, on one hand, is usually described as the "*rarest*" and "*smaller*" variety, but it occurs throughout the entire 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 "*taster*" *pinhão* (Adan et al. 2016; Tagliari and Peroni 2018). We believe that both araucaria reproductive phenology and ethnovarieties characteristics are a consequence of the domestication process and the use of araucaria resources since pre-colonial Amerindians from human groups (Cruz et al. 2020), benefiting and structuring both fauna and flora in the AFS.

The historical forest management in the AFS region for the past 1400 years expanded this forest beyond its natural extent in areas with elevated demography since the pre-colonial period (Robinson et al. 2018). We advocate that the current use and knowledge of araucaria ethnovarieties still shape and maintain this ecosystem productive and preserved under 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 araucaria distribution until 2070 (Castro et al. 2019; Wilson et al. 2019; Marchioro et al. 2020), we might expect that this effect would ruin critical ecological interactions, as well collapsing the actual human-plant interaction.

4.3 Socioeconomic impact and ecosystem services declines

The actual human-plant interaction brings 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 the Brazilian CEASAS (*State Supply Centers*). However, there is an "*informal"* market of *pinhão* trade before arriving at the CEASAS which is not calculated in the historical series. This informal market is mostly linked to local landowners and *pinhão* seller's along Brazilian State highways supplying internal markets in smaller cities, mainly in highlands of southern Brazil and specific regions at *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 *pinhão* value 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 to 85% (Fichino et al. 2017). By exceeding this threshold, uncontrolled *pinhão* harvesting might prevent in both short- and long-term: araucaria regeneration; limitation and reduction of ecosystem services, such as provision (*pinhão* provisioning), support (primary production), and regulation (carbon sequestration) (Fichino et al. 2017).

The very few regulations about *pinhão* harvesting are limited to the beginning of the season extraction (usually from 1st April in Paraná and Santa Catarina states; or 15th April in Rio Grande do Sul; we found no information for São Paulo and Minas Gerais states). However, the majority of extractors usually gather and trade *pinhão* for financial subsistence and food security, and not to guarantee the species conservation, 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 the araucaria seedling suppression (Tagliari and Peroni 2018; Schneider et al. 2018; Quinteiro et al. 2019). It is widely documented the claim of TEK holders to create a mechanism for valuing their interactions and indirect consequences by preserving araucaria (Adan et al. 2016; Tagliari and Peroni 2018; Quinteiro et al. 2019), even though this socioeconomic and ecological interaction in the highly fragmented relics of the Araucaria Forest 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 due to their dependency on climatic conditions (Holland et al. 2017). In the AFS, TEK holders usually live under food insecurity, poverty, and precarious conditions, reinforcing their vulnerability and priority to aidance efforts. The imminent impacts of climate change within the AFS, especially over *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. However, this existing human group also promotes adaptive capacity to reinforce the SES resilience and to reduce its general vulnerability (sensu Holland et al. 2017; Tagliari et al. 2021a). We might witness a combination of threats acting both in short- and long-terms along the Araucaria Forest: unsustainable harvesting; precarious socioeconomic conditions of TEK holders; imminent impact of climate change.

Under climate change, we revealed that the ES provided by Araucaria Forest will undermine and thus compromise human well-being. For instance, the presumed ecosystem services degree can decline by 69.7% from 2070. The ecological network of ES perception by the small landowners based on their TEK also could be threatened due to climate change in all their metrics. Declines in connectance and nestedness — on average of 65% — can indicate that the proportion of links small-landowners recognizing the ESs in the future will decay by at least a half. A similar pattern in the nestedness was found, ensuring the decline of both intraindividual perception of ES and the perception of ES as a group. The increase in modularity can indicate dense connections within the nodes in every cluster in 2070 but with a sparse connection between different notes, i.e. the perception of ES could be shared by sub-groups of people, but not shared by the group as a whole. Empirical evidence indicates a similar pattern in declines of ES and network re-arranges due to mammal defaunation scenarios (Bogoni et al. 2020b). Given that the ecological network is a tool to understand, depict and predict the ecosystem functioning, the species interactions, and the ecological functions (Boccaletti et al. 2006), the SES of Araucaria Forest may disrupt due to climate change.

4.4 Food security and sociocultural interconnection with the Araucaria Forest System

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

Conclusion

5.1 Araucaria Forest contributions to people and people contribution to 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 one is the cornerstone of conservation: Protected Areas (Rodrigues and Cazalis 2020). Within the Araucaria Forest extent, only 10.3% of the more than 1 118 000 km² is encompassed by these areas (Indigenous Territories cover only 0.72% or 8050 km²), where 25% is classified as Strict Protected areas and another 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: the Sustainable Development Reserves (RDS) and Extractive Reserves (RESEX). However, considering the 75% of Sustainable Use areas, only 1.07% is classified as RDS or RESEX, while 72% is classified as Environmental Protection Area (Pacheco et al. 2018), which does not benefit local peoples. This might be a consequence of the Legal Reserves (a private Protected Area) which host another one-third of the remaining remnants of the Atlantic Forest within private properties, such as smallholders' properties. Concerning the araucaria species, only 5 to 10% of its predicted suitable areas in the future (i.e. which are expected to be reduced by ≌70% in 2070) will be encompassed by the existing network of protection (Castro et al. 2019; Marchioro et al. 2020). These suitable areas will be found at more elevated, moister, and 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 priority as a response to climate change is the identification of these potential areas and the necessity to implement new Protected Areas, as well as the creation of both RESEX and RDS Sustainable Use areas.

The second major aspect is targeting the main actors of this Socioecological 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) the valuation of the *pinhão* supply chain; (iii) the maintenance of *pinhão* ethnovarieties; (iv) the mensuration of the ecosystem services provided by remnant areas; (v) the restoration of degraded areas; (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 a 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 is boosted, and, consequently, promote resilience and adaptive capacity to climate change, besides creating positive feedback between TEK holders and the entire socioecological system (Elmqvist et al. 2003; Holland et al. 2017; Tagliari et al. 2021a). Also, by preserving araucaria remnants via TEK holders we find a win-win strategy because there is a possibility to engage more local groups in environmental governance and shorten the distance of 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 ecosystem services perception of TEK holders indicates a profound knowledge and commitment with 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, from top-down (such as restrictive legislation or Strict Use Protected Areas) to bottom-up strategies (such as collaborative-management initiatives with traditional human groups, Payment for Ecosystem Services, or Sustainable Use Protected areas). By considering this integrative scenario, we might reinforce resilience and adaptive capacity to anthropic disturbances of the Araucaria Forest. Otherwise, if we do not seek an integrative response, we might follow the disruption of an extreme and valuable socioecological system to climate change.

Declarations

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6.2 Competing Interests

The authors declared no competing interest.

Author Contributions

MMT conceived the research; all authors reviewed the literature; MMT and JAB wrote the original draft 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 reproduce entirely the outputs of this study is available at GitHub: https://github.com/masemuta/disruption_af. Tables data are freely available at *SIDRA – IBGE* website. Due to ethical aspects, we will provide the ethnoecological data under reasonable request.

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Tables

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

Table 2. The amount of *pinhão* harvesting collected per year (kg * 1000) in the Brazilian states registered at the 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* harvesting collected per year (US$ * 1000) in the Brazilian states registered at the 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

Figures

Figure 1

(a) The Atlantic Forest (dark gray) with the Araucaria Forest ecoregion (green) showing the three Brazilian states which mainly encompass the ecoregion: Paraná (PR), Santa Catarina (SC), and Rio Grande do Sul (RS); **(b)** The Araucaria Forest altitude map and the distribution of Conservation Units: Strictly (yellow) and Sustainable Use Protected Areas (green); black dots represent the occurrence of 97 ethnoecological interviews in this study. Only three interviews occurred at São Paulo state (beyond the Araucaria Forest ecoregion) at Cunha municipality.

Figure 2

The reproductive phenology of the main *pinhão* ethnovarieties throughout the year. The very first ethnovarieties peak production start in March (*"25 de Março*", "*Do Cedo*", "*São José*" until April. The two most cited ethnovarieties – “*Cajuvá*” and “*Macaco*” – peak production start in May until July and from August until December. The *pinhão* production according to all varieties (yellow square) occurs between Mars until December.

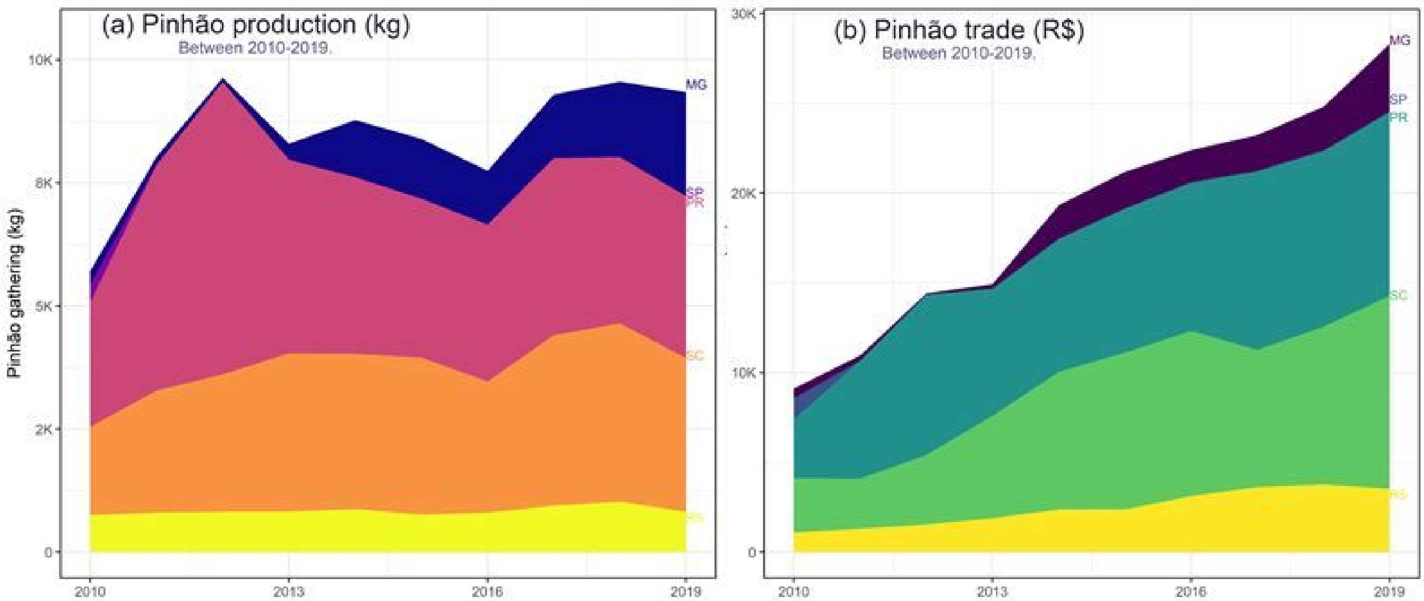

Figure 3

(a) The *pinhão* harvesting (kg) and *pinhão* trade (R$) according to the time-series between 2010-2019. *Pinhão* harvesting indicate that all states collecting *pinhão* might have reached the 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.

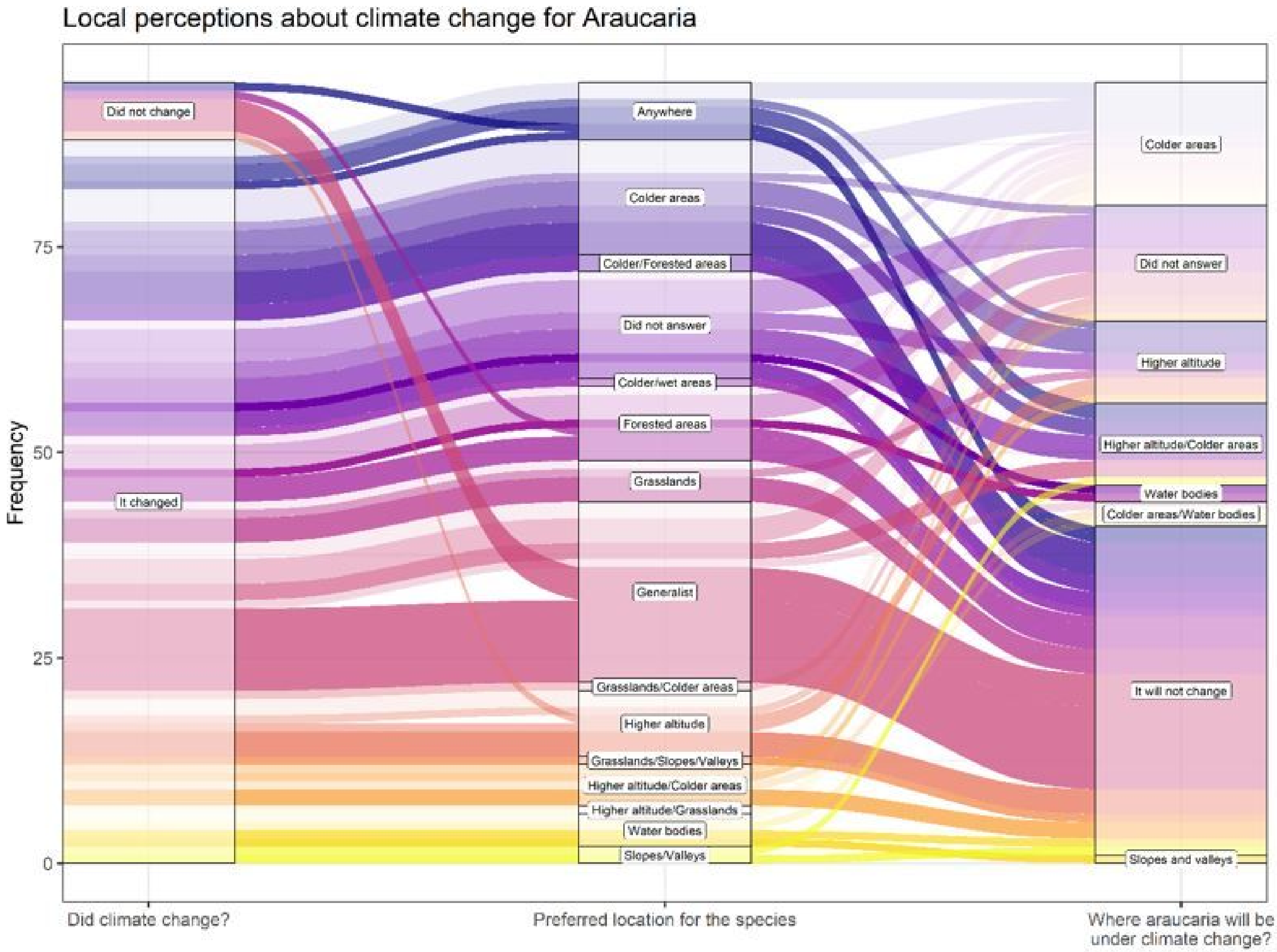

Figure 4

The perceptions of TEK holders about the effect of climate change over araucaria species 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.

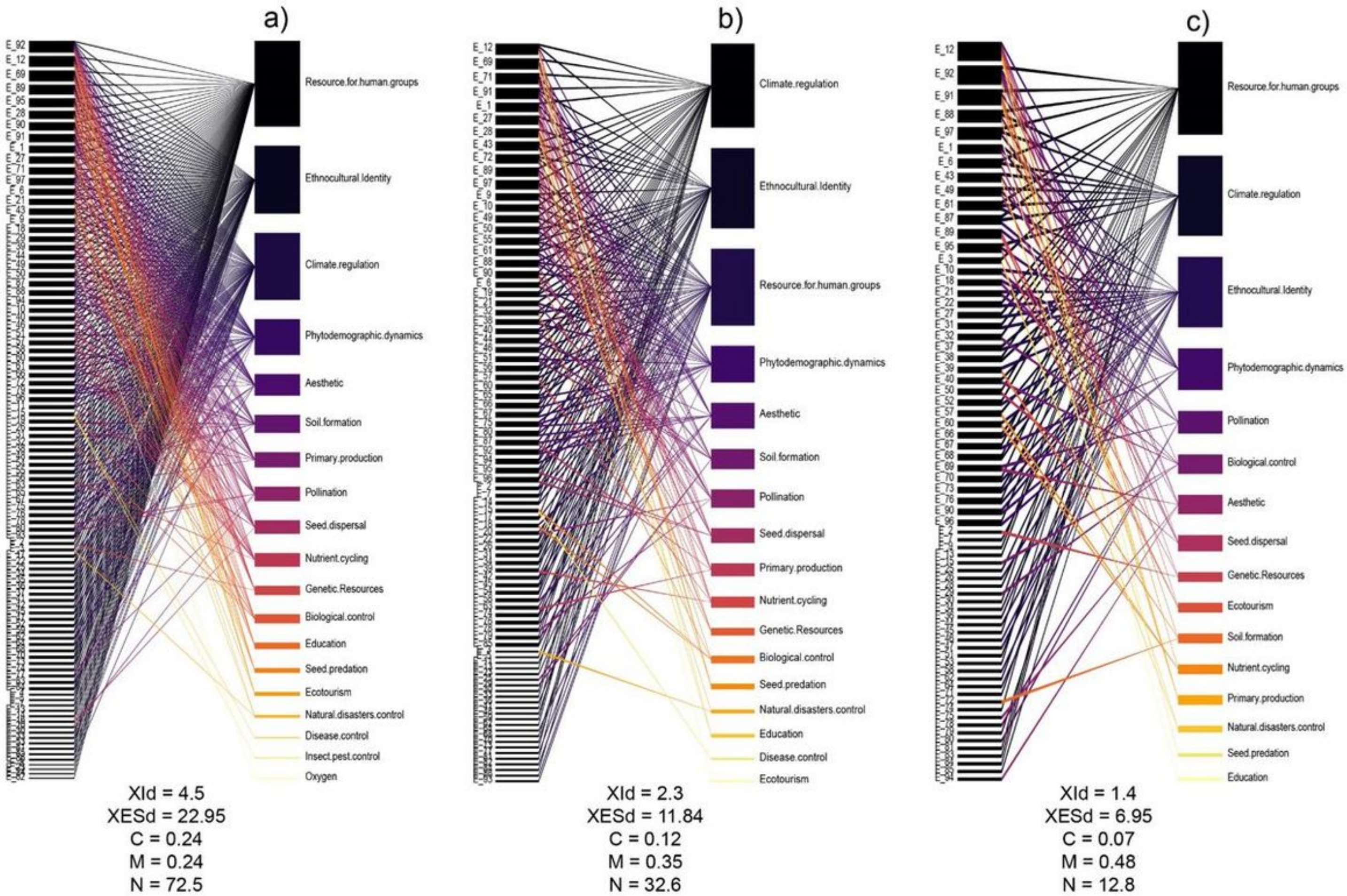

Figure 5

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 people well-being: **(i)** provision (resource for human-groups, seed predation, seed dispersal, phytodemographic dynamics); **(ii)** regulation (climate regulation, disease control, insect pest control, natural disasters 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 of each ecosystem service. To model the potential loss of ecosystem services' perception due to climate change, we combined the outputs of the most recent peer-reviewed studies that estimated the potential area loss for araucaria in 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

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