Cantalice *et al. Journal of Ethnobiology and Ethnomedicine* (2025) 21:5
https://doi.org/10.1186/s13002-025-00757-5

Journal of Ethnobiology and Ethnomedicine

RESEARCH

Open Access

Effects of socioeconomic and human-modified landscape variables on medicinal species richness at a macroscale: the case of the Caatinga, Brazil

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Abstract

Background Ethnobiological studies at local scales have shown that knowledge of medicinal species tends to decrease as socioeconomic status and the extent of human-modified landscapes increase. However, it remains largely unknown whether these same factors can predict knowledge of useful species at broader scales and whether their interaction might create scenarios that enhance knowledge of medicinal species.

Methods To address this, we tested whether knowledge of woody medicinal species—measured as the number of species known—is influenced by socioeconomic status, human-modified landscapes, and their interaction. We compiled and curated data on woody medicinal species from a systematic review encompassing diverse communities across the Caatinga region in North-east Brazil. Using the locations of these communities, we extracted data on socioeconomic status (measured by the Human Development Index, HDI) and human-modified landscapes (quantified as the percentage of forest loss).

Results Our results indicate that forest loss reduces the knowledge of medicinal woody species among Indigenous People and Local Communities. The interaction between human-modified landscapes and socioeconomic status revealed a significant nonlinear relationship, with different combinations yielding varying levels of knowledge about woody medicinal species. Interestingly, socioeconomic status alone does not appear to influence this knowledge. These findings underscore that the processes shaping knowledge of medicinal species differ across scales and suggest the existence of yet unidentified emergent properties that influence medicinal species knowledge at broader scales.

Conclusion The conversion of habitats for anthropogenic use poses a significant risk to the well-being of these populations, as it reduces the availability of species used for prophylactic purposes. In contrast, the cultural traditions of Indigenous People and Local Communities, along with the implementation of regional public policies, may explain why socioeconomic status does not affect local knowledge. Moreover, our study highlights that the processes influencing knowledge of medicinal species at broader scales are not simply the aggregation of local-scale observations. Finally, we propose strategies to advance the field of macroethnobiology.

Keywords Ecosystem services, Macroethnobiology, Seasonally dry forests, Social-ecological systems, Species selection

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Background

The use of plants in disease treatment is a vital component of numerous health systems worldwide [1]. This practice is often associated with the necessity of these resources for subsistence [2] and deeply rooted cultural traditions [3]. The sustained use of natural resources fosters knowledge retention regarding the benefits of biodiversity [4], particularly among Indigenous People and Local Communities (IPLCs) [5]. Some studies suggest that socioeconomic factors such as income, education, and health are associated with knowledge of medicinal plant species. This knowledge can be measured by counting the number of species used by local communities as prophylactic measures [6–9]. However, the dependence on these medicinal resources represents only a fraction of the humans-biodiversity relationship—whether in the acquisition of resources (e.g., food, religious/spiritual practices, ornamentation, and forage) or in the transformation of the environment to meet their needs (e.g., construction of plantations and urban environments). In both scenarios, human-modified landscapes (HMLs) are created. These landscapes dominated by human activities tend to influence the knowledge of IPCLs about medicinal plants [10, 11]. In general, the intensification of human activity has a negative relationship with the knowledge of medicinal species. However, evidence of knowledge loss among IPLCs is primarily derived from local studies, making it unclear whether the effects of HML and socioeconomic status observed at these smaller scales also manifest at broader spatial scales.

The theory predicts that at the individual and community levels [*sensu* Albuquerque et al. [12]], individuals with lower income demonstrate more comprehensive knowledge about medicinal species, as they rely on natural resources for survival [7, 13]. To the best of our knowledge, within metacommunities or macrosystems [*sensu* Albuquerque et al. [12]], it remains uncertain whether the effects of income on knowledge consistently emerge across different communities or regions. Furthermore, a more extended period of schooling decreases people's knowledge about medicinal species, as access to formal education favors knowledge about pharmaceuticals [14, 15]. In fact, the availability of pharmaceuticals and hospitals is negatively associated with the knowledge of medicinal species [7, 16]. Additionally, the transition from natural habitats to HML results in a decline in species knowledge, as it limits the availability of species. This limitation arises either from increased physical distance needed to access animals or plants, particularly arboreal species, or from reduced abundance and local extinctions [17, 18]. Indeed, there is broad consensus that forest loss represents one of the main factors contributing to biodiversity loss from local to global scale [19–22]. Similarly, the loss of natural areas negatively affects native medicinal species [11, 23]. However, socioeconomic status and HML have typically been studied in isolation and within the context of one or a few communities [7, 24, 25]. Their effects, however, may interact synergistically, potentially influencing the knowledge of medicinal species among IPLCs at broader spatial scales.

The potential interplay between socioeconomic factors and HML raises an open question: In regions with minimal HML and higher socioeconomic status, is there a reduced reliance on medicinal species compared to regions with similar levels of HML but lower socioeconomic status? In reality, these interactions are complex and context-dependent, varying significantly across different settings.

The Caatinga, a seasonally dry tropical forest, emerges as an ideal model to test how these variables individually and simultaneously influence the knowledge of medicinal species on a broad scale. The Caatinga is socioeconomically disadvantaged—around 98% of the region has human development indices (HDI) between low and medium [PNAD-National Household Sample Survey in 2020; 26]; as for environmentally—the region has approximately 47,100 fragments distributed across its territory, with the most distinct configurations of sizes and types of land use, thus causing different land use types [27, 28]. This scenario creates pressure on plant resources, mainly tree species due to their high versatility within social-ecological systems—food, fuel (firewood and charcoal), construction, medicine, etc. [29], and availability [30]. Furthermore, IPLCs prefer arboreal species over herbaceous ones in their pharmacopeias due to their availability during droughts [30].

In this study, we investigated the relationships between the knowledge of woody medicinal species in 27 IPLCs, socioeconomic status (measured through HDI income, HDI health, and HDI education), and HML (measured as percentage forest loss) across various regions of the Caatinga, covering approximately 731,000 km^2. In particular, we address the following questions: (1) Do different socioeconomic statuses and human-modified landscapes influence knowledge of medicinal species? (2) Does the interaction between these factors influence the knowledge of medicinal species? We combine studies developed with IPLCs that occupy a vast geographic scale and that have marked differences in their socioeconomic and human-modified landscapes, such as studies close to conservation areas, agroforestry backyards, and rural communities. We aim to address conceptual and theoretical gaps in the knowledge of woody medicinal species at broad spatial scales by investigating potential emerging properties. In this way, this work expands discussions largely based on findings obtained at the local scale that, at times, can be contingent to a specific location. Furthermore, we will address sociocultural issues that involve the security and well-being of a population extremely dependent on these resources.

Methods

Study area

The Caatinga is one of the most biodiverse seasonally dry tropical forests (SDTFs) in the world [31]. Due to the widespread poverty and environmental challenges faced by many populations living in this region, Indigenous People and Local Communities (IPLCs) have developed a strong dependence on natural resources for their subsistence [28, 32, 33]. As populations use natural resources, they create HML, whether due to wood exploration and firewood production, changes to small-scale agriculture, and raising animals such as goats [34]. These HML can decrease the number of native species [35–37]. As a result, it can influence the knowledge of woody medicinal species by reducing their availability [38, 39]. The Caatinga has undergone major land use and cover changes, creating increasingly more HML, with ~ 66% of its environment modified [27, 28]. Currently, the Caatinga is subdivided into 47,100 fragments, of which ~ 91% have areas smaller than 500 ha [27].

Database

Ethnobiological

The ethnobiological data were obtained from a systematic review of 75 articles focused on woody medicinal plants in the Caatinga [40]. In these studies, each interviewee served as a sampling unit, responding to questionnaires about the medicinal species they knew. Given the absence of individual-level data, such as lists of species known by each respondent, we used the final list of species from each study to represent the community's collective knowledge of woody medicinal species richness. In this context, these lists are considered as pharmacopeias—the sets of known medicinal species within each community. Considering that the use of a species implies prior knowledge, we standardized the term as 'knowledge', since some studies do not clearly differentiate between 'use' and 'knowledge'.

To align the review results with our objectives, we applied the following selection criteria: (a) inclusion of the location or geographic coordinates of the studied communities; (b) exclusion of studies focusing exclusively on a single species, taxonomic group, or pharmacological purpose (e.g., articles limited to medicinal species from the Fabaceae family or those used to treat heart diseases); (c) inclusion of a list comprising at least ten medicinal species; (d) proper identification of the species, with specimens incorporated into a herbarium; and (e) location of the studied communities within the Caatinga phytogeographic region. After this filtering process, we collected the following information: (a) location or geographic coordinates of the communities; (b) year of publication of the article; (c) medicinal species used, identified by their scientific names; and (d) number of respondents, which served as a measure of sampling effort.

Socioeconomic variables

We used two approaches to collect socioeconomic data: first, we collected HDI (i.e., Human Development Index, hereafter referred to as HDI) information in a grid with a resolution of 5 *arc-min* between 1990 and 2015 [41], and we overlaid it with the geographic coordinates of each community using the '*extract*' function of the '*raster*' package [42]. The values of the HDI vary from 0 to 1, where 0 represents the lowest possible level of development and 1, is the maximum level. The HDI can still be classified as low (< 0.5), medium (0.5 to 0.79), high (0.8 to 0.89), or very high (> 0.9)—for each base community in the year of publication of the article. For works published after 2015 (n=3), we used the HDI of 2015 as a reference, as it is the closest value to the year of publication (*see* Supplementary Material–Fig. S1). In the second approach, we gathered information on HDI income, HDI education, and HDI longevity, *sensu* of 2010 [26] (Supplementary Material–Fig. S1). We then cross-referenced this data with the geographic coordinates of each article to obtain the values of these variables at the municipality level.

Land use and cover

We collected land use and coverage data from MapBiomas—Collection 7 (https://plataforma.brasil.mapbiomas.org) using *Landsat* images in raster format of the Caatinga phytogeography, with a resolution of 30 m, covering the years 2000 to 2019 [43]. We used the geographic coordinates of the communities as centroids to create 5 km buffers (Fig. 1). These buffers were used to crop the Caatinga rasters, considering the years of publication of each article. We produced images of land use and cover considered the year of publication of the manuscripts. Subsequently, with the new images, we used the '*lsm_c_ca*' function from the '*landscapemetrics*' package [44] to classify the land use and cover types of the studied communities. The classifications were predefined by MapBiomas [43]. After classification, we identified 12 classes, five (41.66%) of which were non-anthropic: forest formation; savannah formation; grassland formation; rivers and lakes; and rocky outcrop; and seven (58.34%) anthropic: pasture; mosaic of uses; other non-vegetated areas; urbanized

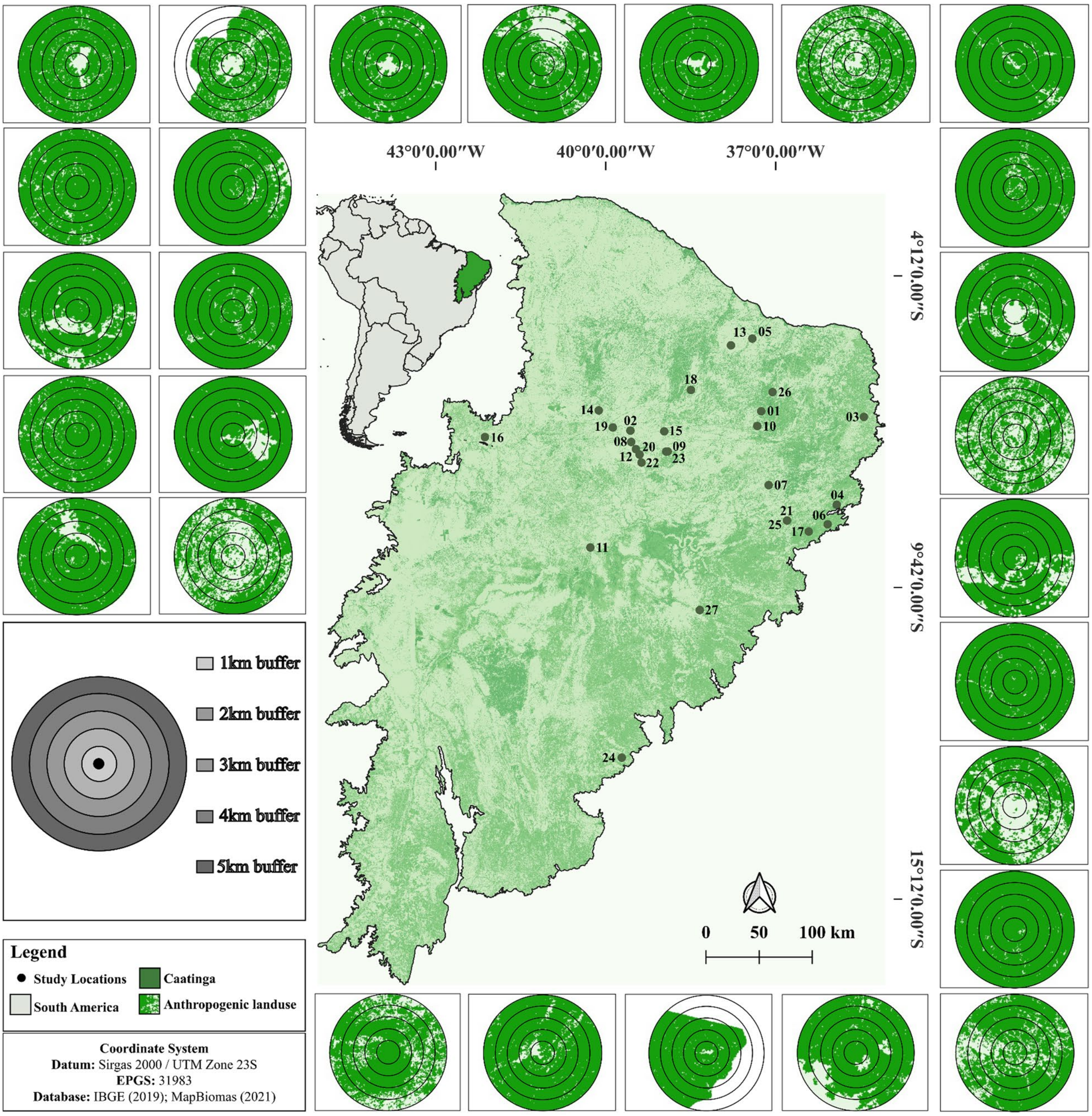

Fig. 1 A location map (see Supplementary Material 1) indicates the points of the studied communities in Caatinga, Brazil. Communities are represented counterclockwise, with anthropic areas highlighted in gray and non-anthropic areas in green. Within each representation, black circles depict buffers ranging from 1 to 5 km

area; other temporary crops; sugar cane; and other perennial crops (see Supplementary Material–Table S1). Subsequently, we aggregated the anthropic areas to calculate the total percentage of areas modified by humans—forest loss (see Supplementary Material–Fig. S2). This metric, hereafter referred to as human-modified landscapes, varies from 0 (landscape with minimal human activity visible) to 100% (completely anthropic).

Data analysis

We employed a Generalized Additive Model (GAM) to test how forest loss and HDI influence knowledge of woody medicinal plants in the Caatinga. The GAM was chosen because it allows the estimation of smooth and nonlinear relationships without specifying the functional form [see [54]]. We used the '*gam*' function to fit our model, including the HML, along with the '*s*' function to specify that it would be modeled with smooth splines (which indicate a nonlinear relationship) and '*ti*' to model interactions between variables through tensor products of smoothing functions. As differences in sampling effort can affect the estimated number of species [46], we used the number of respondents in each study with the '*offset* (log)' function in the model. This offset was used to account for the potential influence of the number of respondents on estimates of the richness of known medicinal woody species, thus functioning as a fixed effect in the model (see Supplementary Material–Table S2). We use the '*gam.check*' function to check the adequacy of the model fit (e.g., distribution of residuals and outliers), and the specifications of the '*k*' function model. Finally, we simplified the models by removing the predictor variables and using the '*anova.gam*' function to find the best model, based on the AIC values. All functions used in this model are from the '*mgcv*' package [45].

We employed a generalized linear model (GLM) with a negative binomial distribution to examine how HDI income and HDI health influence the knowledge of woody medicinal plants in the Caatinga. The negative binomial GLM was selected to address overdispersion observed in models using Poisson and quasi-Poisson distributions. The number of respondents in each study was incorporated into the model using the '*offset* (log)' function. For this, we used the '*glm.nb*' function from the '*MASS*' package [47] (see Supplementary Material–Table S2). During the model construction, we chose to remove the education variable due to its high correlation with income (cor = 0.69, $p < 0.05$). Correlation values between variables were obtained using the '*rcorr*' function from the '*Hmisc*' package [48]. To check the model assumptions, we used the '*simulateResiduals*' function from the '*DHARMa*' package [49]. Analyzes were performed using the R software [50].

Sensitivity analysis

The spatial scale decision impacts estimates of broad-scale variables, such as relationships between the number of species and landscape variables [more details 51]. We built concentric buffers from 1 to 4 km of radius (Supporting Information S1) to verify whether the extracted human-modified landscapes (HMLs) at different extensions influence the knowledge of medicinal species. Then, we repeated the generalized additive models (GAMs) described above to test the influence of HML on the knowledge of woody medicinal species in the Caatinga using different buffer extensions. To check whether different spatial extensions better answer our question, we used the R^2*adjust* value as a model selection criterion, thus obtaining the best effect scale for our model [51] (see Supplementary Material–Table S2; Fig. S3).

Results

Our study was based on 27 articles published between 2000 and 2019. Local pharmacopeias ranged between 11 and 33 (mean = 21.6 ± 7SD) woody medicinal species as for HML varied between 3.9% and 88.4% (36.55 ± 22.52). Human development index (HDI) ranged from 0.62 to 0.71 (0.68 ± 0.02), and the values associated with income varied between 0.49 and 0.70 (0.59 ± 0.05), education 0.42 and 0.67 (0.54 ± 0.07), and longevity 0.68 and 0.82 (0.79 ± 0.04).

Our analysis revealed that HML reduced the number of medicinal woody species known by local communities by approximately 40% ($F=0.430$; $p=0.038$; Table 1; Fig. 2). In contrast, the socioeconomic status of these communities was not directly associated with the number of known species (Table 1; Fig. 2). Additionally, we identified a nonlinear interaction between socioeconomic status and HML that influenced species knowledge ($F=1.709$; $p=0.027$; Table 1; Fig. 2).

Our findings suggest that different combinations of these factors can either increase (e.g., 0.68 HDI and 76% forest loss) or decrease (e.g., 0.62 HDI and 62.5% forest loss) the knowledge of woody medicinal species. The model accounted for 39.1% of the variation in the number of medicinal plant species (R^2adj = 0.30). Contrary to

Table 1 Generalized additive model (GAM): number of medicinal woody species as a function of the human development index (HDI) and human-modified landscapes (forest loss), including the interaction between these variables

	Estimate	Std. error	*t* value	*p*-value
socioeconomic—HDI	− 14.62	57.76	0.253	0.803
	edf	***Ref. df***	***F statistic***	***p-value***
s(HDI)	1.35	14	0.430	**0.038**
ti(HDI, forest loss)	1.37	16	1.709	**0.027**
Intercept coefficient = 25.56 ± 39.09	Adjusted r^2 = 0.30; Deviance explained = 39.1%			

The parameters '*s*' and '*ti*' represent different smoothing functions used in GAM. The '*s*' parameter defines individual smoothing terms in the model formula, while the '*ti*' parameter is used to model interactions between variables through tensor products of smoothing functions

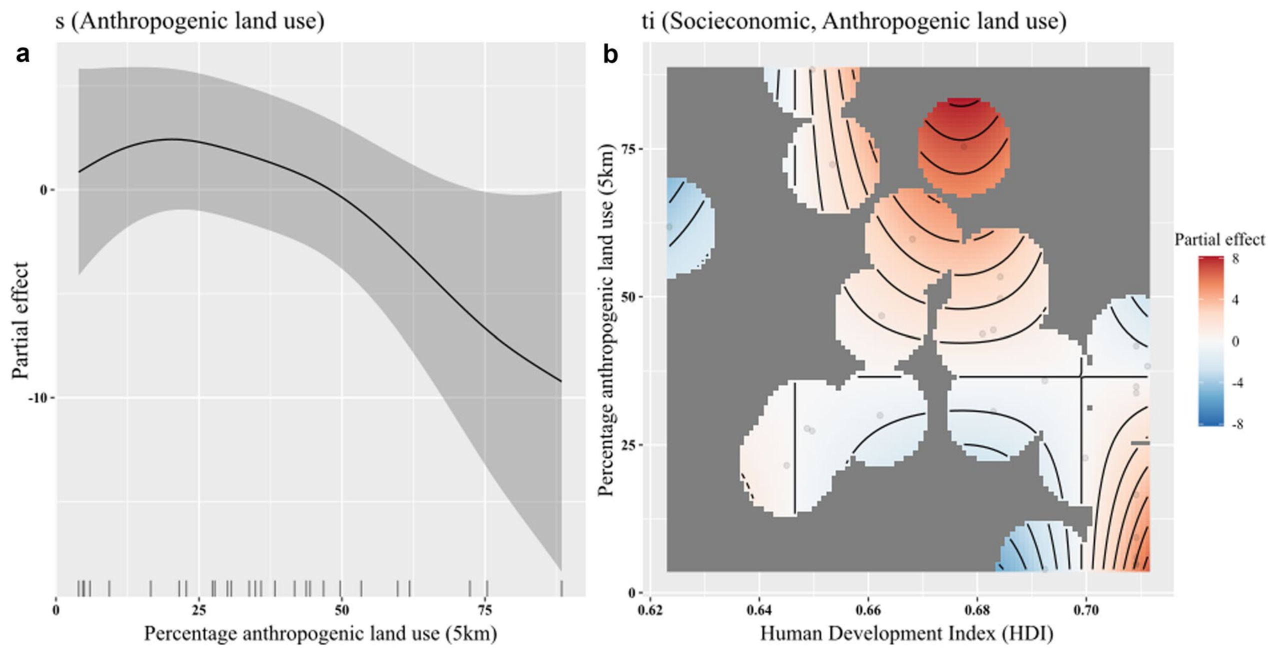

Fig. 2 GAM models illustrate the partial effect of the number of medicinal woody species in the Caatinga on **a** human-modified landscapes, and **b** the interaction between socioeconomic status and human-modified landscapes. The shaded areas in each model indicate the 95% confidence interval; More information can be found in Supporting Information S1

Table 2 Generalized linear model (GLM), showing the relationship between the number of medicinal woody species and the human development index (HDI) in their income and health partitions

	Estimate	Std. error	*t* value	*p*-value
income HDI	0.08	1.52	0.056	0.955
health HDI	0.89	1.84	0.485	0.628
Intercept coefficient = 2.28 ± 1.24		Adjusted $r^2 = 0.021$		

our expectations, no significant relationships were found between HDI income, HDI health values, and the richness of woody medicinal species ($p > 0.05$; Table 2; Fig. 2).

Discussion

Our study demonstrates that human-modified landscapes (HMLs) negatively impact local community knowledge of woody medicinal species. Specifically, greater human modification of landscapes results in fewer woody species being included in pharmacopeias—the set of species used as prophylactic measures for both physical and spiritual illnesses by local populations. Furthermore, we observe a nonlinear relationship involving the interaction between HML and socioeconomic status, indicating that different combinations lead to an increase or decrease in knowledge of woody medicinal species. However, we also found that socioeconomic status, related to income, health, and education did not influence the knowledge of woody medicinal species on large scales.

Our findings reveal a nonlinear relationship between the knowledge of woody medicinal species and land use intensity at broad scales, with a notable reduction in the number of known species as forest loss increases. In highly HML, the reduction of natural areas restricts the availability of medicinal species and, consequently, access to these resources by local populations [10, 11, 17]. This trend is particularly concerning given the ongoing transformation of natural habitats into HML—approximately 25.6% of the biome's total area has undergone anthropization in the past 37 years [43]. This is especially critical considering the dependence of populations in the Caatinga on woody species to form their local pharmacopeias [29, 52]. In semiarid regions, communities prioritize the use of woody species, as they remain available throughout the year, particularly during dry periods [30].

Furthermore, medicinal species from the Caatinga are characterized by their low redundancy, that is, species do not usually share multiple therapeutic targets—the way local populations perceive diseases; and high versatility, that is, the species are used in different areas—timber, food, fuel, etc [32, 53, 54]. These aspects could increase the vulnerability of the local medical system to disruptions [53, 55]. It is important to note that, although we used the year of publication as a proxy for the timing of ethnobiological data collection in relation to the context of resource use and land cover in communities, we acknowledge the potential anachronism between these datasets. This limitation arises because the exact timing of data collection is rarely reported in the articles.

Our findings revealed that socioeconomic status, encompassing income, health, and education, did not exhibit a correlation with the knowledge of medicinal species at a broad scale. This finding contradicts results observed at local scales, which typically show a decrease in the number of medicinal species as income, education, and access to healthcare increase [6, 7, 9, 16]. To explain this discrepancy, we propose two more parsimonious scenarios. First, the cultural tradition of local communities in the Caatinga region regarding the use of medicinal species plays a pivotal role. This deeply rooted tradition likely contributes to the persistence of medicinal species in local pharmacopeias, irrespective of socioeconomic status. These communities may also be hybridizing their prophylactic practices [see Hybridization 55]. Several studies highlight that communities often use both medicinal species and biomedical treatments simultaneously, demonstrating a degree of independence from external factors, whether socioeconomic or environmental [8, 57, 58].

Second, public assistance programs, such as **Bolsa Família**, have been implemented in the region to provide financial support to families living in poverty or extreme poverty. The Bolsa Família program provides income transfers to families with a monthly per capita income below R$ 218.00 (approximately USD 35.26, based on an exchange rate of 6.07 BRL per USD). The program conditions benefit eligibility on compliance with requirements that promote access to health and education for children, integrating these efforts with other public policies [59]. The North-east region, where the Caatinga is located, has been one of the main beneficiaries, showing significant socioeconomic improvements, particularly in access to schools, electricity, medicines, and treated water [60, 61]. The implementation of such assistance programs serves as a positive driver for improving local well-being [62, 63]. Additionally, these programs may influence the integration of medicinal resources into local practices [64], potentially fostering the hybridization of medical systems [56]. This hybridization reflects a blending of traditional medicinal species use with biomedical approaches, further supporting the resilience of local pharmacopeias.

Therefore, it is important to emphasize that our analysis had the community as the sampling unit. At the same time, ethnobiological work uses data at the individual level, which is extremely rare at larger scales. We recognize the anachrony between socioeconomic and ethnobiological data, especially in general HDI data. Our results should be interpreted with caution due to uncertainties associated with sample size, even though we attempted to account for this effect by incorporating the number of individuals interviewed. Additionally, it is crucial to consider the context in which such studies are typically conducted—often focusing on "rural" populations and those with low socioeconomic status [see [65]].

Finally, our results indicate that the interaction between different HML and socioeconomic status influences the increase or decrease in knowledge about woody medicinal species. In this sense, even in environments with high forest loss and high socioeconomic levels, where a decrease in knowledge of woody medicinal species would be expected, the number of known species can be high. In other words, the processes involved in structuring large-scale pharmacopeias are not just the sum of variables at local scales. This relationship underscores that the selection of species for pharmacopeia is non-random. For instance, preferences for specific species and their utilization across diverse therapeutic categories, such as respiratory and digestive ailments, may constrain the exploration of novel species [29].

Moreover, cultural factors may drive the pursuit of woody medicinal species independently of socioeconomic status and shifts in HML. For example, local markets often feature trade-in barks and leaves of these plants, contributing to the diversity of recognized medicinal species [66]. This discovery reinforces the understanding that knowledge of medicinal species on a broad scale is closely related to the availability of species in the environment. This finding reinforces that large-scale knowledge of medicinal species is closely related to their availability in the environment. Furthermore, the discovery that the interaction between socioeconomic status and HML is not synergistic and that socioeconomic status does not influence large-scale knowledge highlights the existence of still unknown emerging properties.

Recommendations and conclusions

Our study also raises important reflections for ethnobiological research: (a) the comparison between urban and rural environments as indicators of HML, since environments classified as rural, does not always reflect low levels of HML and vice versa. This does not reflect the availability of species; (b) the inclusion of welfare policies in models that test the relationship between socioeconomic status and knowledge of medicinal species, since we do not know how public policies connect to local knowledge; (c) the need for open data, whether ethnobiological or social. In this sense, we hope that future studies can consider these issues.

Our study revealed that increasing the HML is negatively associated with reduced pharmacopeias in local populations. If the current trend of converting natural landscapes into human-modified ones persists, local populations may face significant challenges in accessing resources necessary for disease treatment, potentially leaving them unassisted. This can lead to processes of hybridization, diversification, or incorporation of exotic species into medical systems. Furthermore, our result shows that regardless of socioeconomic status, people know and use medicinal species; that is, the search for conservation of these species should not be restricted to environments with lower socioeconomic status.

Abbreviations

HDI	Human development index
HML	Human-modified landscapes
IPLCs	Indigenous People and Local Communities
SDTF	Seasonally dry tropical forests
GAM	Generalized additive model
GLM	Generalized linear model

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13002-025-00757-5.

Additional file 1.

Acknowledgements

The authors would particularly like to thank the members of the Laboratory of Ecology and Evolution of Social-ecological Systems (LEA) and Laboratory of Ecological Synthesis and Biodiversity Conservation (ECOFUN), for the conversations and exchange of knowledge that helped in the construction of the manuscript. ASC extends sincere appreciation to the Coordination for the Improvement of Higher Education Personnel (CAPES), Code nº 001.

Author contributions

ASC contributed to conceptualization, data curation, formal analysis, writing—original draft, and writing—review and editing. TGS was involved in data curation, formal analysis, and writing—review and editing. UPA performed conceptualization, writing—original draft, and writing—review and editing. All authors gave final approval for publication and agreed to be held accountable for the work performed.

Funding

Contribution of INCT Ethnobiology, Bioprospecting, and Conservation of Nature, certified by CNPq, with financial support from FACEPE (Foundation for the Support of Science and Technology of the State of Pernambuco; Process Number: APQ-0562–2.01/17.

Availability of data and materials

All relevant information for the replication of the study that is not included in the text, along with additional details, is available in the Supporting Information.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable

Competing interests

The authors declare no competing interests.

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Received: 5 November 2024 Accepted: 10 January 2025
Published online: 24 January 2025

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