The human fingerprint of medicinal plant species diversity

Nawal Shrestha[1,2*], Robbie Hart[3,4], K. David Harrison[4,5], Lorène Gourguillon[6], and Charles C. Davis[1,7,8*]

[1]Department of Organismic and Evolutionary Biology, Harvard University Herbaria, Cambridge, Massachusetts 02138, USA

[2]Department of Agriculture, School of Science, Kathmandu University, Dhulikhel, Kavre, Nepal

[3]William L. Brown Center, Missouri Botanical Garden, St. Louis, MO 63110, USA

[4]Center for Plants, People, and Culture, New York Botanical Garden, Bronx, NY, USA

[5]VinUniversity, Hanoi, Vietnam

[6]LVMH Recherche, 185 Avenue de Verdun, 45800 Saint Jean de Braye, France

[7]Department of Biology, Washington University in St. Louis, St. Louis, MO, USA

[8]Missouri Botanical Garden, St. Louis, MO, USA

*Email for correspondence: cdavis@oeb.harvard.edu

Medicinal plants have long been crucial to human civilizations, supporting both traditional and modern healthcare systems. However, the processes influencing the global diversity and distribution of medicinal plants remain underexplored. Their diversity, like that of other species groups, is shaped by abiotic and biotic influences, which include, in unique ways, human ecological (including cultural) practices. Here, we investigate and compare these influences on the distribution and diversity of 32,460 medicinal plant species and on global vascular plant distributions. We identify significant regional variation in medicinal plant diversity, including "hotspots" (India, Nepal, Myanmar, and China) and "coldspots" (Andes, New Guinea, Madagascar, the Cape Provinces, and Western Australia) of unrealized diversity. Human migratory timelines have significant influence on medicinal plant diversity and distributions, underscoring the likely importance of accumulated ethnobotanical knowledge over time. Regions with long histories of human settlement typically boast more diverse medicinal floras than expected. In contrast, language diversity, an indicator of cultural diversity, appears to have a limited direct effect on medicinal plant diversity, but its indirect effects warrant further exploration. Our study emphasizes the need for integrated conservation strategies that incorporate both standard ecological factors and human ecological dimensions; the latter are critical for preserving medicinal plant resources and enhancing global healthcare solutions.

Medicinal plants have been integral to human cultures for millennia and have played a central role in the development and expansion of societies (*1*). These plants represent a global biodiversity heritage that is essential for both traditional and modern healthcare systems. Medicinal plants are pivotal for ongoing pharmaceutical research and drug development (*1-3*), contribute to ecosystem health (*4*), and support myriad cultural traditions and the global economy (*4-6*). Notably, around 80% of the Global South relies exclusively on medicinal plants, and approximately 25% of Western pharmaceuticals are derived or inspired by plants and fungi (*3, 7*).

The sustainable use and conservation of medicinal plants depend heavily on precise species distribution data and a comprehensive understanding of their spatial patterns and related abiotic and biotic influences. Conservation of medicinal plants also depends on the survival of indigenous cultures and the traditional knowledge they contain. Indigenous peoples currently steward over 25% of the world's land surface and 37% of remaining natural lands (*8*). Ethnobotanical studies demonstrate that a large share of vernacular names and known medicinal uses of plants may be found only in indigenous languages which are themselves endangered (*9-12*). Thus, both scientific and traditional knowledge are crucial for maintaining biodiversity, protecting ecosystem services, and unlocking the benefits of medicinal plants for future advancements in healthcare (*1, 4*). Despite their importance, however, a systematic understanding of the broad distribution of medicinal plants and the processes influencing their diversity and distribution remains in its infancy.

In a recent ground-breaking investigation, Pironon *et al.* (*13*) identified a strong correlation between vascular plant diversity and the diversity of plant species used by humans, including medicinal species. Their findings demonstrated that medicinal plant diversity largely mirrors overall plant diversity, with regions rich in vascular plants also boasting significant medicinal plant diversity. However, drivers of the diversity and distribution of medicinal plants involve not only abiotic factors, traits, and interspecific interactions, but also human ecological practices. For example, cultural norms and knowledge systems found in Indigenous languages are known to influence plant use and its diversity (*14, 15*); regions with high cultural diversity for which linguistic diversity may serve as a proxy (*16, 17*) often also have diverse medicinal plant practices. However, global and regional assessments of medicinal plant diversity rarely include the likely influence of human sociocultural dynamics (*16-23*).

A key unexplored topic is whether variation in the duration of human interactions with a flora has influenced regional heterogeneity in medicinal plant knowledge and diversity. Different regions have been inhabited by modern humans (*Homo sapiens*) for different lengths of time (*24*); Africa, for example, was occupied ≈200,000–150,000 years ago (*25*), whereas *H. sapiens* arrived in the Americas ≈16,000–15,000 years ago (*26, 27*). Such differences may have impacted the extent to which medicinal plants were experimentally discovered, used, and integrated into traditional knowledge systems in different regions. For instance, South African Zulu healers use 1,142 medicinal plants (*12, 28*), whereas Belizean Mayan healers use 659 medicinal plants (*9*).

Our central hypothesis is that longer human occupancy fosters a greater accumulation of traditional knowledge and cultural use of local plant species for healing purposes, leading to higher medicinal plant diversity. To our knowledge, the imprint of regional occupancy times on current medicinal plant knowledge and diversity remains untested.

Here, our primary objectives are to [i.] identify broad patterns in medicinal plant diversity and examine their correlation with vascular plant distributions at regional and global scales and [ii.] investigate how medicinal plant diversity patterns are related to two key human ecological factors: cultural diversity (using language diversity as a proxy) and the duration of human occupancy. Our aim is to enhance understanding of the complex interplay between climate, overall vascular plant diversity, and human ecology in shaping the global distribution and diversity of medicinal plants. Such knowledge is crucial for recognizing the impacts of environmental and cultural changes on biodiversity, and for the conservation and sustainable use of medicinal plants in improving human health.

Uncovering substantial regional variation in medicinal plant diversity

We conducted a comprehensive analysis of global medicinal (N = 32,460) and vascular plant species (N = 357,008), mapping their diversities across 369 botanical countries (spatial units defined by the World Geographical Scheme for Recording Plant Distributions (*29*), table S1). Plant species data were sourced from the Medicinal Plant Names Services (MPNS) version 12 (https://mpns.science.kew.org/) and the World Checklist of Vascular Plants (WCVP)(*30*). Consistent with Pironon *et al*. (*13*), our results demonstrate that medicinal plant diversity generally aligns with the latitudinal distribution of vascular plants, peaking in tropical regions (figs. 1 and S1) (*20, 31*). However, there are intriguing departures from this general trend. The well-documented very high vascular plant diversity is accompanied by unusually low medicinal plant diversity in both New Guinea (with the highest language diversity in the world (fig. s2)) and Madagascar (with low language diversity) (figs. 1 and S1).

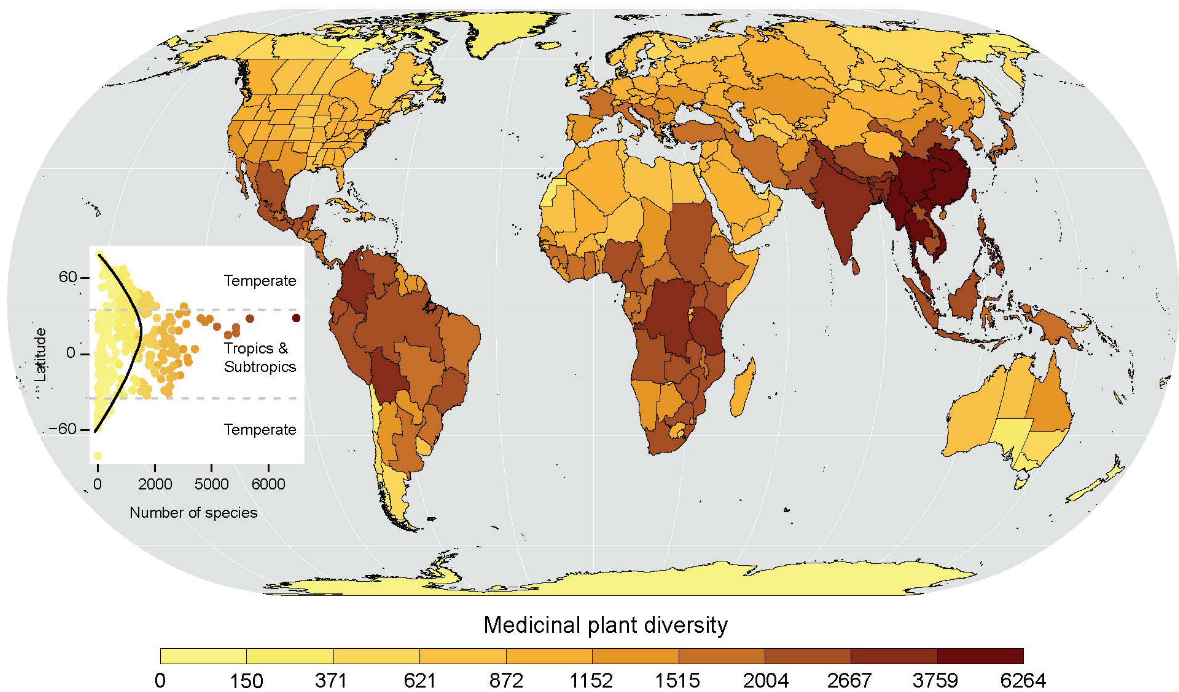

Figure 1. Global distribution of medicinal plant species. The map illustrates medicinal plant species diversity, with darker shades representing higher diversity and lighter shades indicating lower diversity levels. The inset depicts the latitudinal trend, highlighting the highest species diversity in tropical regions, consistent with the latitudinal diversity gradient. The black solid line represents a locally weighted scatterplot smoothing (LOWESS) regression. The map is presented using an Eckert IV projection.

To further assess regional variations, we analyzed medicinal plant diversity across botanical countries grouped into six widely accepted phytogeographic regions (25): Afrotropic, Australasia, Indomalaya, Nearctic, Neotropic, and Palearctic. Our one-way ANOVA results indicated significant regional variation in medicinal plant diversity ($F_{5,327}$ = 22.82, P < 0.001), with Tukey's HSD post-hoc tests revealing notable differences between regions (fig. S3). Indomalaya, despite comparable vascular plant diversity to the Neotropics (fig. S1), exhibits significantly higher medicinal plant diversity (P < 0.05) (fig. S3), underscoring that vascular plant diversity alone does not account for observed differences (*13*). Our linear model (medicinal plant diversity as the response variable and vascular plant diversity as the predictor), which included phytogeographic region as an interaction term, revealed a significant interaction effect between vascular plant diversity and region ($F_{5,326}$ = 28.62, P < 0.001), implying that region *per se* has a notable influence on the relationship between vascular and medicinal plant diversity. Our regional models corroborated this finding, further revealing significant differences in the strength of the relationship between vascular and medicinal plant diversity across regions (fig. 2). The Indomalaya region exhibits the steepest slope between vascular and medicinal diversity (fig. 2), indicating that an increase in vascular plant diversity results in greater medicinal diversity gains in Indomalaya compared to other regions. In contrast, Australasia exhibits the least steep slope, indicating lower overall medicinal diversity gains compared to other regions.

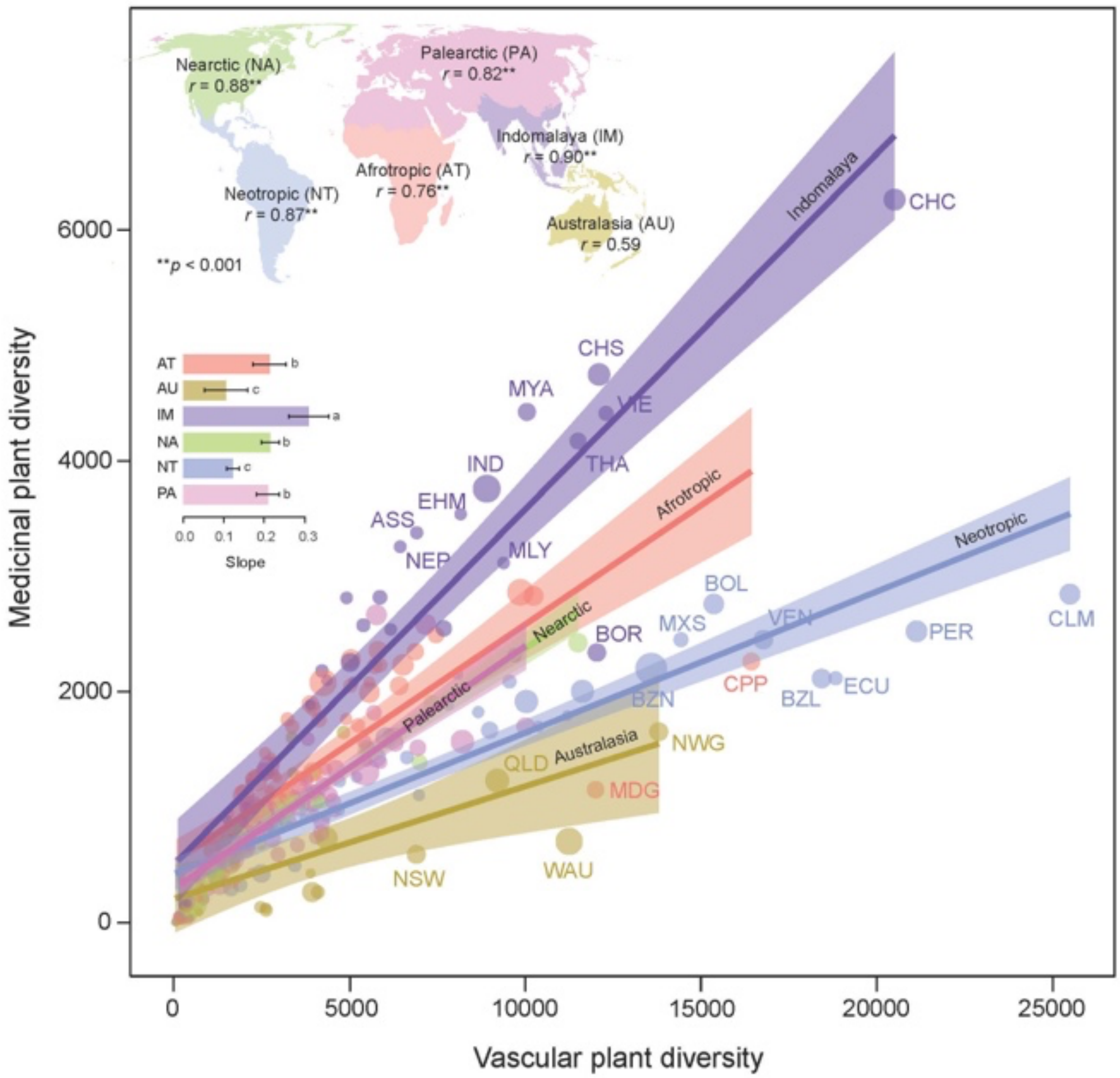

Figure 2. Comparative analysis of vascular and medicinal plant diversity across biogeographic realms. Each dot's size reflects the area of six color-coded phytogeographic regions, with larger dots indicating larger areas of botanical countries. The three-letter codes next to each dot represent botanical countries (refer to table S1 for details). Pearson's correlation coefficients (*r*) for the relationship between vascular and medicinal plant diversities are displayed for each realm. The bar on the left illustrates the slopes and 95% confidence intervals of this relationship across the six realms. Bars with different letters (a, b, c) indicate significant differences ($p < 0.05$), determined using Bonferroni correction for pairwise comparisons.

Our investigation into deviations from predicted medicinal plant diversity revealed “hotspots” and “coldspots” of medicinal plant diversity (fig. 3). Regions like India, Nepal, Myanmar, and China show higher than predicted diversity (two-tailed test, $P < 0.05$). At the same time, the Andes, Cape Provinces, Madagascar, Western Australia, and New Guinea demonstrate lower than expected medicinal plant diversity (two-tailed test, $P < 0.05$) (fig. 3).

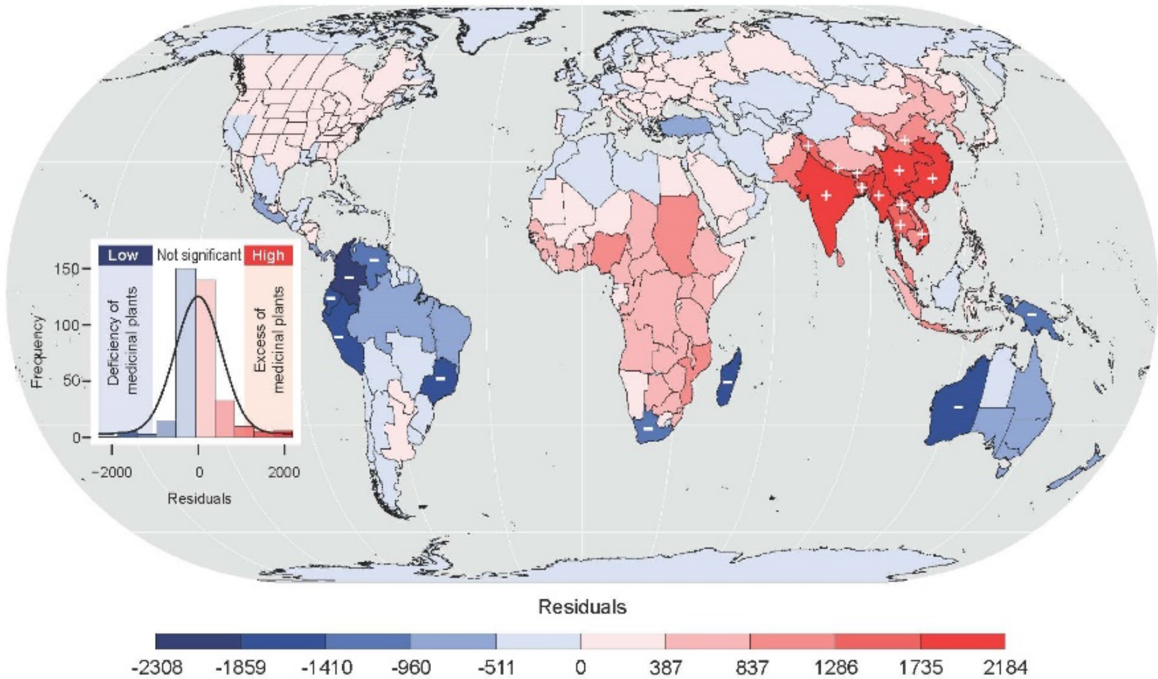

Figure 3. Residual analysis of medicinal versus vascular plant diversity. The map displays residuals from the linear regression comparing medicinal plant diversity to vascular plant diversity. Red indicates positive residuals, suggesting a surplus of medicinal plants, whereas blue indicates negative residuals, reflecting a deficiency. Botanical countries with significantly higher or lower medicinal plant diversity than expected ($p < 0.05$) are marked with plus (+) and minus (-) signs, respectively. The map uses an Eckert IV projection.

We acknowledge that these regional patterns may partially reflect disparities in research and documentation efforts. Canonical medicine systems like Ayurveda (*32*) and Traditional Chinese Medicine (*33*), which reflect extensive accumulated traditional knowledge, may increase the number of recorded uses of medicinal plant species. In contrast, colonial influences and modernization may have contributed to the further erosion or non-recording of this knowledge (*34*), thus highlighting the need to better preserve and explore traditional ethnobotanical practices. For example, the decline of traditional knowledge, as seen in Ecuador relative to Peru (*35*), underscores the importance of cultural heritage in maintaining medicinal plant diversity. Finally, we recognize that differing phylogenetic histories and speciation rates may influence these patterns beyond cultural factors. Despite these caveats, our global findings may stem from variation in ethnobotanical knowledge and cultural practices (*14, 15*) that remain untested and should be investigated.

Human arrival time and its association with medicinal plant diversity

We also explored the relationship between medicinal plant diversity and potential climatic and anthropogenic predictors using a linear mixed-effect model. This model included seven fixed-effect predictors (fig. S4) and treated the phytogeographic region as a random effect to account for variations across regions. Beyond the known climatic predictors of plant diversity (*20-23*), we included human occupancy time (fig. S5) and language diversity (fig. S2), which is often used as a proxy for cultural diversity correlated with ethnobotanical knowledge (*16, 17*), to test our hypothesis that earlier human presence fosters the development of traditional medicine systems, the cultivation of medicinal plants, and an ultimate increase in overall regional medicinal plant diversity.

Our results confirmed the strong influence of vascular plant diversity on medicinal plant diversity (fig. S4). Human occupancy time emerged as the second-most significant predictor. These associations remained robust to uncertainties in estimating human occupancy times (fig. S6), suggesting that the observed relationships are not artifacts of estimation errors. This suggests that vascular plant diversity does have an influence on medicinal plant diversity, but the length of human engagement within a particular environment—perhaps via experimentation and traditional practices—is pivotal in determining medicinal plant usage. These results raise the hypothesis that over time, human societies within a region experiment with, and recognize the medicinal value of, various plants, thereby enhancing diversity through shared knowledge and discoveries. As most languages are unwritten, this botanical knowledge is largely orally transmitted, reinforced by cultural learning and frequent interactions with plants (*9, 11*).

To test for these interactions among human ecological predictors, we used path ("causal") models at both global and regional scales. These models aligned with our mixed-effect model results and identified direct and indirect effects (*36*). Both vascular plant diversity (standardized path coefficient = 0.66; $P < 0.001$) and human occupancy time (standardized path coefficient = 0.22; $P < 0.001$) significantly affect medicinal diversity globally and regionally (figs. 4 and S7). Human occupancy time significantly explained the variation in medicinal plant diversity (standardized path coefficient = 0.34; $P < 0.001$) even after controlling for the effect of vascular plant diversity (fig. S8), highlighting the substantial role of human occupancy time in shaping medicinal plant landscapes beyond commonly explored factors.

Limited impact of language diversity on medicinal plant diversity

Although our mixed-effect model identified a significant global effect of language diversity on medicinal plant diversity (fig. S4), the path model did not support a direct relationship between these two variables at the same scale (fig. 4). This discrepancy highlights the structural differences between these models. Linear models focus on direct interactions, capturing the apparent significance of language diversity without accounting for complex intermediaries. In contrast, path models explore intricate interdependencies, incorporating indirect effects via mediating variables like climate (*36*). This suggests that language diversity might indirectly influence medicinal plant diversity, mediated by environmental factors significantly correlated with language and vascular plant diversity (see fig. 4). Language diversity and biodiversity are linked (*16, 17, 37*) and mutually reinforcing due to shared environmental influences and indigenous knowledge networks (*38, 39*).

Biodiversity-rich areas often foster diverse cultures with unique languages, as diverse ecological resources support both biological and cultural diversity. These environmental conditions may drive both biological and cultural evolution, allowing species and languages to flourish. Our path model identifies this dependency, suggesting that there are likely more complex dynamics between medicinal plant and language diversity.

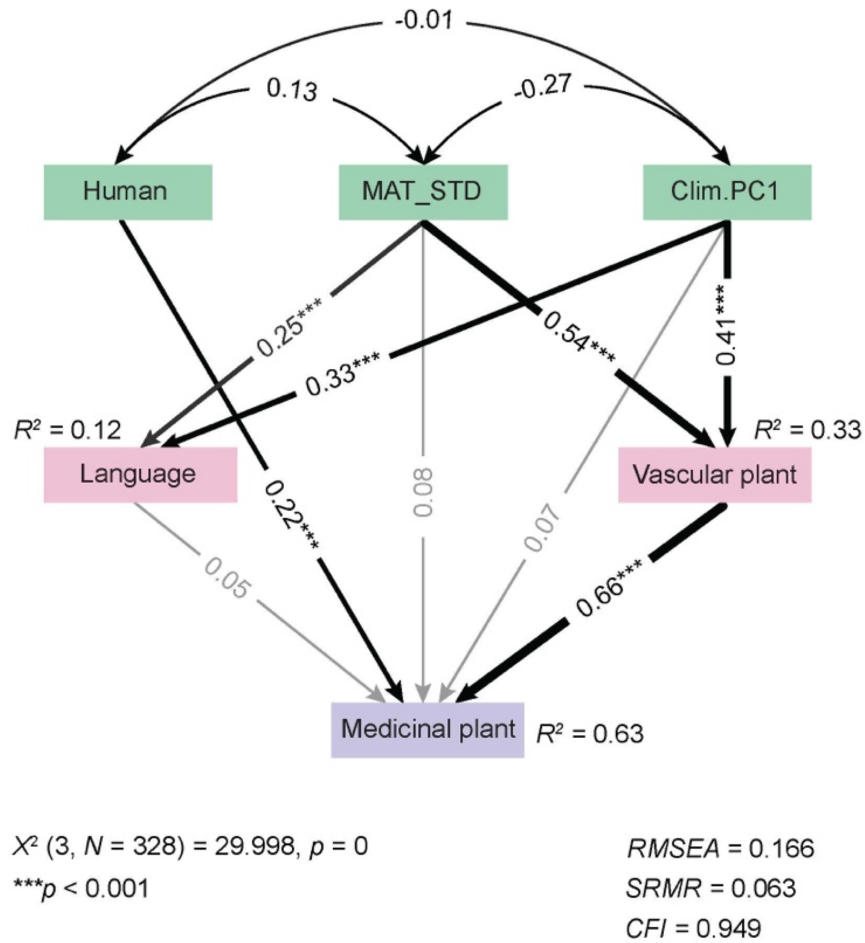

Figure 4. Path model depicting influences on medicinal plant diversity. This model illustrates the relationships among climate, environmental heterogeneity, earliest human colonization, language diversity, and vascular plant diversity in explaining medicinal plant diversity. Standardized path coefficients are indicated along the paths. Variables include Human: Time of first modern human colonization; MAT_STD: Standard deviation of mean annual temperature; Clim.PC1: First principal component of 19 bioclimatic variables. Fit indices provided are RMSEA: Root mean square error of approximation, SRMR: Standardized root mean square residual, and CFI: Comparative fit index.

Conclusions

Our analysis identifies a likely pivotal role for human ecology in shaping global medicinal plant diversity. Although vascular plant diversity remains the primary correlate of medicinal plant diversity, our findings reveal that human occupancy time also significantly and directly influences medicinal plant diversity. This suggests that longer human occupancy fosters accumulated traditional knowledge, the use of local plants for medicine, and the emergence of local experts such as healers or shamans, resulting in increased medicinal plant diversity. Our results highlight the need for integrated approaches that consider both “natural” and anthropogenic factors in understanding plant distributions. Regions we identified as medicinal diversity coldspots, such as the Andes, New Guinea, Madagascar, the Cape Provinces, and Western Australia, certainly have unrecorded or unrecognized medicinal plant resources. Conversely, regions such as India, Nepal, Myanmar, and China are hotspots of medicinal plant diversity and should be formally recognized as biodiversity hotspots and prioritized for systematic preservation and in-depth scientific research. Finally, although we did not find a direct impact of language diversity on medicinal plant diversity, its indirect effects through shared environmental factors suggest complex interdependencies worth further exploration. Preserving ethnobotanical knowledge, especially in language hotspots (*40*), is crucial for maintaining and enhancing medicinal plant diversity. These insights are vital for fostering sustainable conservation strategies and leveraging the untapped potential of medicinal plants in addressing future healthcare challenges (*1*).

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Competing interests: CCD and LG declares that they are supported by LVMH Research and Dior Science, a company involved in the research and development of cosmetic products based on floral extracts. CCD also serves as a member of Dior's Age Reverse Board.

Data and materials availability: The native distribution dataset of global vascular plant species used in the current study has been deposited in Zenodo (*41*) except for the MPNS dataset, which was obtained from Kew under CC-BY-NC license, with an additional restriction against sharing with third parties. The gridded environmental data, language data and human occupancy data, including the R codes used for data analysis and visualization is hosted on GitHub (*42*).

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