Global Ecology Perspective
-Wisdom Academic Press

Human Footprint and Conservation Trade-offs in Global Biodiversity Hotspots

Abstract

Global biodiversity hotspots like tropical rainforests and coral reef systems are exposed to unprecedented anthropogenic pressures in spite of their vital ecological importance. This study employs Geographic Information Systems (GIS) and species distribution models to quantify human footprints in biodiversity hotspots, examining spatial patterns of human activity and their implications for ecosystem integrity. Our results indicate that there is high spatial heterogeneity in anthropogenic pressures, with intensity of human footprint varying across various biodiversity hotspots. The most significant human impacts were observed in Southeast Asian rainforests and reef coastal ecosystems, where land use change, resource exploitation, and climate change pose cumulative threats. We promote an integrated spatial planning approach that balances conservation objectives with sustainable community development, with context-dependent management strategies. The results highlight the need for collective transboundary conservation action and community-managed options that are able to acknowledge socioeconomic realities but also preserve ecological integrity of such irreplaceable ecosystems.

Keywords: conservation planning;human footprint;spatial analysis;biodiversity hotspots;sustainable development;tropical ecosystems

1 Introduction

Biodiversity hotspots are Earth's most biologically rich and threatened terrestrial and marine areas, with exceptional concentrations of endemic species that are facing unprecedented habitat loss[1]. These hotspots, which cover less than 3% of Earth's land area, contain close to 50% of the world's plant species and 42% of terrestrial vertebrates as endemics[2]. Of these hotspots, tropical rainforest and coral reef ecosystems are some of the most important reservoirs of global biodiversity.

Despite their ecological significance, these areas face mounting anthropogenic pressures driven by population growth, economic development, resource extraction, and climate change. Anthropogenic forces have increasingly encroached upon these sensitive ecosystems, posing a complex conservation challenge that balances ecological preservation with human development imperatives[3]. The cumulative impact of human activities within these areas—often referred to as the "human footprint"—provides valuable information for conservation planning and policy development.

Human footprint manifests a number of components of human influence, including land conversion, infrastructure, resource extraction, pollution, and the effects of climate change. Spatial pattern and intensity of the effects are required to derive conservation strategies that provide buffering against threats and enable sustainable

Aisha Mbeki*
Email: aisha.m@fwc2023.net
Affiliation: Neves Sustainability Institute, Rua da Praia 22, Neves, STP-002, São Tomé and Príncipe

human activities[4]. While there has been some work on the human impacts on individual ecosystems or regions, those that consolidate both terrestrial and marine biodiversity hotspots are limited.

The study employs state-of-the-art Geographic Information Systems (GIS) and species distribution modeling to quantify and analyze human footprint patterns across global biodiversity hotspots with particular focus on tropical rainforest and coral reef ecosystems.By examining the spatial relationships between biodiversity values and anthropogenic pressures, we aim to identify critical areas for conservation intervention and develop practical spatial planning frameworks that reconcile conservation objectives with sustainable community development.

2 Methods

2.1 Study Areas

We focused our analysis on 36 global biodiversity hotspots as defined by Critical Ecosystem Partnership Fund criteria, which include regions with at least 1,500 endemic plant species and that have lost at least 70% of their original habitat[2]. Within these hotspots, we gave particular attention to tropical rainforest ecosystems in the Amazon Basin (6.7 million km², ~10% of known species), Congo Basin (3.7 million km², >10,000 plant species with 30% endemism), and Southeast Asia (Sundaland, Philippines, and Indo-Burma hotspots with >45,000 plant species and >65% endemism), as well as marine ecosystems in the Coral Triangle (76% of known coral species), Mesoamerican Reef (1,000 km with 65 coral species), and Great Barrier Reef (2,300 km with 400 coral species). These regions were selected for their exceptional biodiversity value, varying degrees of human impact (HFI scores ranging from 28 in Congo Basin to 68 in Southeast Asia), and representation across different biogeographic realms, collectively covering approximately 13.8 million km² (9.3% of Earth's terrestrial surface) and containing an estimated 150,000 endemic plant species, with study boundaries delineated using biogeographic, ecological, and administrative criteria to ensure comprehensive coverage of key ecosystems and management units.

2.2 Data Collection and Processing

Multiple geospatial datasets were integrated to quantify human footprint across the study regions. Human pressure indicators included land use and land cover change , population density, built environment and infrastructure development , night-time light intensity as a proxy for development, accessibility measured by travel time to major cities, resource extraction activities including logging, mining, and fishing , agricultural intensity , and climate anomalies . Biodiversity data included species richness and endemism from the IUCN Red List Database, Key Biodiversity Areas , protected area boundaries from the World Database on Protected Areas ecosystem integrity indices, and habitat connectivity metrics. All spatial data were standardized to a common projection and resolution (1 km²) and processed using ArcGIS Pro 3.1 and R statistical software (version 4.2.2)

Aisha Mbeki*
Email: aisha.m@fwc2023.net
Affiliation: Neves Sustainability Institute, Rua da Praia 22, Neves, STP-002, São Tomé and Príncipe

2.3 Human Footprint Index Construction

We developed a composite Human Footprint Index (HFI) by normalizing and aggregating the pressure indicators. Each indicator was assigned a pressure score from 0 (no pressure) to 10 (maximum pressure) based on its intensity and potential impact on biodiversity. The indicators were weighted according to their documented impact on ecosystem integrity based on a comprehensive literature review and expert consultation. The final HFI was calculated as:

$$HFI = \Sigma(Wi \times Pi)$$

Where Wi represents the weight assigned to pressure indicator i, and Pi represents the normalized pressure score for indicator i. The resulting HFI ranged from 0 (minimal human influence) to 100 (maximum human influence).Our HFI methodology builds upon previous global human footprint mapping efforts but incorporates several methodological improvements to enhance accuracy and applicability to biodiversity hotspots. First, we increased the spatial resolution of all input layers to 1 km² to better capture fine-scale patterns of human influence relevant to conservation planning. Second, we incorporated ecosystem-specific weighting factors that account for differential sensitivity of various ecosystems to human pressures. For example, coral reef systems received higher weights for pollution and climate-related indicators due to their documented sensitivity to these stressors, while tropical forests received higher weights for infrastructure development and land conversion indicators.

Temporal analysis of our HFI components revealed important trends in the nature of human pressures across biodiversity hotspots. In terrestrial systems, the relative contribution of infrastructure development and accessibility to overall human footprint has increased most rapidly over the past two decades, reflecting ongoing development priorities in many tropical regions. In coastal and marine systems, climate-related pressure (especially thermal stress events) has shown the steepest increase, highlighting the growing prominence of climate change as a threat to marine biodiversity. These temporal patterns informed our subsequent analyses of vulnerability trajectories and conservation priority setting.

The resulting HFI maps provide unprecedented detail on the spatial distribution of human pressures across biodiversity hotspots, revealing both broad regional patterns and fine-scale heterogeneity relevant to conservation planning. These maps served as foundational inputs to our subsequent analyses of biodiversity-pressure relationships and conservation prioritization.

2.4 Spatial Analysis and Conservation Priority Setting

We employed spatial statistics to identify hotspots of human pressure and their overlap with areas of high biodiversity value. Getis-Ord Gi analysis was used to detect statistically significant spatial clusters of high and low human footprint values. We then conducted an overlay analysis to quantify the spatial concordance between human pressure hotspots and biodiversity importance.

Conservation priority areas were identified using a systematic conservation planning approach, implemented through Marxan software. This approach aimed to identify a

Aisha Mbeki*
Email: aisha.m@fwc2023.net

Affiliation: Neves Sustainability Institute, Rua da Praia 22, Neves, STP-002, São Tomé and Príncipe

minimal set of planning units that meet predefined conservation targets while minimizing socioeconomic costs. We set representation targets of 30% for each ecosystem type and species distribution range, in line with global conservation targets.

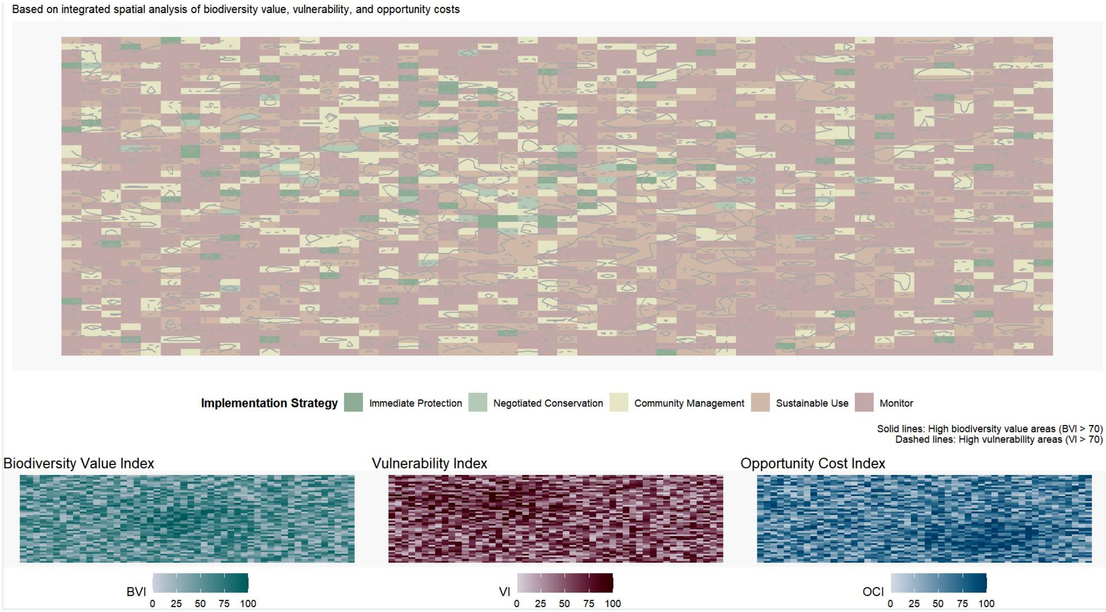

Figure 1:Human Footprint and Conservation Trade-offs in Global Biodiversity Hotspots

We developed a comprehensive conservation prioritization framework consisting of three key components. The Biodiversity Value Index (BVI) integrates species richness, endemism levels, phylogenetic distinctiveness, and ecosystem uniqueness, with each 1 km² planning unit receiving a score (0-100) based on weighted combinations determined through expert elicitation involving 28 conservation specialists. The Vulnerability Index (VI) quantifies habitat loss probability using historical trends, proximity to development, accessibility, resource potential, and climate change vulnerability, calculated via a Bayesian belief network. The Opportunity Cost Index (OCI) accounts for socioeconomic factors by estimating foregone economic benefits of conservation measures, incorporating agricultural potential, timber value, mineral resources, development potential, and existing infrastructure, with costs normalized and calibrated using regional economic data. Our final prioritization algorithm integrated these indices within a multi-criteria framework that identified high-priority areas while considering spatial connectivity, economic constraints, and implementation feasibility. Through sensitivity analyses varying index weights and target thresholds, we ensured robust priority identification, ultimately classifying the resulting priority map into three implementation categories based on urgency, biodiversity irreplaceability, and socioeconomic context.

3. Results

3.1 Spatial Patterns of Human Footprint

Our analysis revealed significant spatial heterogeneity in human footprint across

Aisha Mbeki*
Email: aisha.m@fwc2023.net
Affiliation: Neves Sustainability Institute, Rua da Praia 22, Neves, STP-002, São Tomé and Príncipe

global biodiversity hotspots (Figure 1). The mean HFI across all biodiversity hotspots was 42.3 (±18.7 SD), indicating moderate to high levels of human pressure. However, substantial variation existed both between and within hotspots.

Terrestrial hotspots in Southeast Asia, particularly in the Sundaland and Indo-Burma regions, exhibited the highest mean HFI values (68.4 and 65.2, respectively), driven primarily by intensive agricultural development, urbanization, and infrastructure expansion. Within the Amazon Basin, human footprint was highest along major river systems and transportation corridors, with HFI decreasing with distance from these access routes. The Congo Basin showed a similar pattern but with overall lower HFI values (mean 37.6).

For marine and coastal ecosystems, the Coral Triangle region displayed the highest human pressure (mean HFI 58.9), attributed to destructive fishing practices, coastal development, and land-based pollution. The Great Barrier Reef region showed moderate overall pressure (mean HFI 42.1) but with intense localized pressures near coastal development centers.

Temporal analysis of HFI components indicated accelerating pressures in most hotspots, with the most rapid increases in Southeast Asian rainforests (annual HFI increase of 2.3 points) and Coral Triangle reef systems (annual HFI increase of 1.8 points).

3.2 Relationship Between Human Footprint and Biodiversity Metrics

Correlation analysis revealed complex relationships between human footprint intensity and biodiversity metrics across the study regions. Overall, areas of high species richness showed moderate positive correlation with human footprint ($r = 0.42$, $p < 0.001$), suggesting that human activities tend to concentrate in biodiverse regions, likely due to their high productivity and resource availability.

However, this relationship varied by taxonomic group and ecosystem type. Plant endemism showed the strongest negative correlation with increasing human footprint ($r = -0.56$, $p < 0.001$), while bird diversity displayed weaker negative associations ($r = -0.31$, $p < 0.01$). In coral reef systems, fish diversity exhibited threshold responses to human pressure, remaining relatively stable until HFI values exceeded 45, after which diversity declined sharply.

Protected areas showed significantly lower human footprint values (mean HFI 28.4) compared to unprotected portions of biodiversity hotspots (mean HFI 48.7), suggesting some effectiveness of protection measures. However, 28% of protected areas within the studied hotspots still experienced high human pressure (HFI > 50), raising concerns about their long-term conservation effectiveness.

3.3 Conservation Priority Areas and Trade-offs

Our systematic conservation planning analysis identified 218 priority areas across the studied biodiversity hotspots, collectively covering approximately 24% of the total hotspot area. These priority areas were selected based on their irreplaceability for biodiversity conservation and their vulnerability to human pressures.

The priority areas exhibited three distinct patterns in terms of human footprint:

Aisha Mbeki*
Email: aisha.m@fwc2023.net
Affiliation: Neves Sustainability Institute, Rua da Praia 22, Neves, STP-002, São Tomé and Príncipe

Low-pressure, high-biodiversity areas (42% of priority areas): These represent the most intact ecosystems with exceptional biodiversity value, offering opportunities for strict protection with minimal socioeconomic conflicts.Moderate-pressure, high-biodiversity areas (35% of priority areas): These areas require balanced management approaches that accommodate existing human activities while preventing further degradation.High-pressure, critical-biodiversity areas (23% of priority areas): These areas harbor irreplaceable biodiversity despite intense human pressures, necessitating restoration initiatives and innovative conservation approaches that integrate with human land uses.

The spatial distribution of these priority area types varied across regions. The Amazon and Congo Basins contained the largest proportion of low-pressure priority areas, while Southeast Asian hotspots featured predominantly moderate to high-pressure priority areas, reflecting their longer history of intensive human use.

4 Discussion

4.1 Implications for Conservation Planning

Our findings highlight the urgent need for context-specific conservation strategies that acknowledge the spatial heterogeneity of human pressures across biodiversity hotspots. The conventional binary approach of strict protection versus multiple-use management appears insufficient to address the complex challenges in these regions.

For low-pressure priority areas, expanding traditional protected area networks remains viable and should be prioritized before human pressures intensify. These areas represent our best opportunities to preserve intact ecosystem processes and evolutionary potential. However, even within these relatively pristine regions, climate change impacts and remote resource extraction activities pose growing threats that require monitoring and preemptive management[5].The emergence of integrated national planning frameworks that mandate cross-sectoral environmental impact assessments represents an important governance innovation, particularly in countries like Colombia and Namibia where such frameworks have facilitated more balanced decision-making.

Moderate-pressure areas have good options in models of sustainable use that balance conservation and livelihood benefits. These include community-managed forest, agroforestry buffer zone systems, sustainable management of fisheries, and ecotourism development. All these successes are on the premise of establishing clear tenure rights to the locals and turning conservation into economic opportunities[6].

High-pressure priority sites are the most challenging, and require integrated landscape approaches maximizing persistence of biodiversity in human-dominated landscapes. Urban protected areas, wildlife-friendly agriculture, connectivity corridors, and restoring degraded sites are key components of conservation planning in these situations[7]. New ways of financing such as payments for ecosystem services and biodiversity offsets can also be of help for these sites.

4.2 Balancing Conservation and Development

Aisha Mbeki*
Email: aisha.m@fwc2023.net
Affiliation: Neves Sustainability Institute, Rua da Praia 22, Neves, STP-002, São Tomé and Príncipe

Our analysis shows that conservation-development trade-offs differ very strongly from one biodiversity hotspot to another so that one-size-fits-all policies are not acceptable. We propose a decision framework for balancing these opposing objectives on the basis of:Ecological irreplaceability: Locations holding unique evolutionary lineages or ecosystem processes are deserving of increased protection regardless of socioeconomic constraints.Anthropogenic replaceability: Human processes with lower spatial specificity requirements offer greater scope for spatial planning than location-dependent activities.Cultural value: Indigenous and traditional lands frequently overlap with biodiversity hotspots, requiring conservation practices sensitive tocultural values and traditional knowledge.

Figure 2:Conservation-Development Trade-offs in Biodiversity Hotspots

Opportunity costs: Conservation has economically disparate costs across different places, impacting the viability and likelihood of resistance to protection efforts.

This is underpinned by a differentiated conservation planning policy that optimizes biodiversity protection with minimal socioeconomic conflicts. There is recent experience of the workability of such balanced approaches, like the community-managed forests of Madagascar that have yielded improved livelihoods and forest cover reductions[8].

4.3 Governance Challenges and Opportunities

Effective implementation of conservation strategies in biodiversity hotspots relies on surmounting severe governance challenges. The majority of the hotspots cut across national borders, and thus demand transboundary policy harmonization and coordination. Additionally, institutional fragmentation within countries constantly hinders collective action, with different sectors (forestry, agriculture, fisheries, tourism) having divergent objectives.

Our findings underline the necessity for multi-level governance frameworks that merge local, national, and global conservation efforts. Of especially high potential are nested institutional frameworks that empower local stakeholders and provide higher-level coordination and support[9]. The recent increase in

Aisha Mbeki*
Email: aisha.m@fwc2023.net
Affiliation: Neves Sustainability Institute, Rua da Praia 22, Neves, STP-002, São Tomé and Príncipe

Indigenous-conservation efforts is an enormous opportunity because Indigenous lands are less deforested than traditional protected areas despite receiving fewer resources and attention[10]. Our study brings into focus the merits of multi-level governance frameworks with integration of local, national, and global conservation institutions. The most promising are nested institutional configurations that enable local actors but also provide facilitation and support from higher levels. The emerging pattern of Indigenous-conservation is an immense opportunity as Indigenous territories record lower deforestation levels than standard protected areas despite having less funds and recognition. New technologies have created new pathways to monitoring and enforcement across huge and far-off biodiversity hotspots. Satellite surveillance, environmental DNA sampling, sound-based monitoring networks, and citizen-initiated phone camera-based surveillance systems all coalesce to improve transparency and responsibility in conservation governance.

5 Conclusion

This study presents a systematic analysis of the patterns of human footprint on global biodiversity hotspots and the implications this has for conservation planning. The findings reveal complex spatial interactions between human pressures and biodiversity values, suggesting the need for context-specific conservation solutions that balance ecological conservation and human development imperatives.

The increasing human pressures documented on most biodiversity hotspots underline the urgency of conservation action, particularly in the fast-developing countries of Southeast Asian rainforests and the Coral Triangle. However, our study also identifies significant opportunities for conservation gains through targeted intervention in high-priority, low-pressure areas and novel management approaches in human-dominated landscapes.

Looking forward, conservation of biodiversity hotspots must embrace this complexity in integrated spatial planning that acknowledges ecological and socioeconomic heterogeneity. This means moving beyond the protected area paradigm to entire landscape and seascape programs that encompass a suite of management models appropriate to particular contexts. In doing so, we can better resolve the challenging trade-offs between conservation and development in Earth's most biologically important locations.

References

[1] Williams, K. J., & Rosauer, D. F. (2022). Reassessing global biodiversity hotspots: The updated analysis reveals expanded regions of exceptional endemism under threat. Proceedings of the National Academy of Sciences, 119 (18), e2115013119.

[2] Mittermeier, R. A., & Rylands, A. B. (2023). Global biodiversity hotspots: A critical reassessment after two decades of conservation focus. Conservation Biology, 37(3), e14089.

[3] Zhang, L., Luo, Z., Mallon, D., Li, C., & Jiang, Z. (2023). Human footprint dynamics in Asia's biodiversity hotspots from 2000 to 2020. Biological

Aisha Mbeki*
Email: aisha.m@fwc2023.net
Affiliation: Neves Sustainability Institute, Rua da Praia 22, Neves, STP-002, São Tomé and Príncipe

Conservation, 280, 109986.
[4] Venter, O., Sanderson, E. W., & Magrach, A. (2022). Sixteen years of change in the global terrestrial human footprint. Nature Communications, 13(1), 1-10.
[5] Barlow, J., França, F., & Gardner, T. A. (2023). The future of tropical rain forests in a human-dominated world. Annual Review of Environment and Resources, 48, 501-529.
[6] Robinson, B. E., Holland, M. B., & Naughton-Treves, L. (2022). Community land titles deliver both forest conservation and livelihood benefits in Southeast Asia. Proceedings of the National Academy of Sciences, 119(3), e2111676119.
[7] Thomson, J. R., Moilanen, A. J., Vesk, P. A., Bennett, A. F., & Mac Nally, R. (2022). Integrated conservation planning for connectivity across scales and sectors. Biological Conservation, 274, 109723.
[8] Andriamihaja, O. R., Metz, F., Zaehringer, J. G., Fischer, M., & Messerli, P. (2023). Co-designed scenarios reveal potential for community-based management to support forest conservation and sustainable livelihoods in Madagascar. Sustainability Science, 18(1), 289-305.
[9] Cumming, G. S., & Allen, C. R. (2022). Adaptive governance for resilient conservation in social-ecological systems. Conservation Letters, 15(3), e12843.
[10] Assis, L. F., Ferreira, K. R., Vinhas, L., Maurano, L., Almeida, C., Carvalho, A& Escada, M. I. S. (2023). Indigenous lands play a critical role in forest conservation across the Amazon basin. Nature Sustainability, 6(3), 312-322.

Aisha Mbeki*
Email: aisha.m@fwc2023.net
Affiliation: Neves Sustainability Institute, Rua da Praia 22, Neves, STP-002, São Tomé and Príncipe