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Editorial

This issue once again takes readers on a journey through a wide variety of protected areas, highlighting both the challenges they face and the approaches being developed to address them. The topics covered further enrich the growing eco.mont knowledge base and contribute to a better understanding of conservation and management issues in protected mountain regions worldwide.

To facilitate access to the wealth of information published in eco.mont, we have expanded the resources available on the journal's homepage. The eco.mont database (https://www.mountainresearch.at/ecomont/mountain-data-explorer/) allows users to search all articles published to date by keywords and phrases, with direct links to the corresponding PDFs.

For the Alpine community, we have also integrated the ALPARC map of protected areas into the eco.mont website (https://www.mountainresearch.at/ecomont/articles-on-protected-areas-in-the-alps/). Protected areas that have been featured in eco.mont articles are marked on the map, making it easy to explore published research geographically.

The articles in this issue reflect the diversity of themes, regions and management challenges currently shaping research on protected areas. They range from assessments of ecological change and biodiversity conservation to questions of sustainable management and governance, offering valuable insights from mountain protected areas around the world.

In the article *Potential of Use of Remote Sensing Data as an Additional Management Tool in Biosphere Reserve Networks – A Case Study of Czech Biosphere Reserves*, Petr Cupa and Petr Vahalik explore the use of CORINE Land Cover data as a supplementary management tool. By assessing the ecological stability of biosphere reserves in the Czech Republic, the authors demonstrate how remote sensing data can support informed decision-making and strengthen collaboration between researchers and practitioners.

In *Carbon Sequestration Potential of the Dibudalan Mountain Forest Reserve, Philippines*, Afed Daiwey highlights the ecological significance of this tropical forest reserve and emphasizes the need for effective forest management strategies to enhance the protection of its biodiversity and carbon storage potential.

The Zillertal Alps High Mountain Nature Park Anchored in the Region by Dedication of All Involved by Valerie Braun, Willi Seifert, Gudrun Steger, Paul Steger, Annemarie Polderman and Katharina Weiskopf offers insights into the development and management of a protected area. The article traces the park's establishment and evolution over time and highlights the importance of local participation, inter-institutional cooperation and strategic communication in fostering acceptance and ensuring long-term success.

In *Sustainable Heritage: Protecting Jingmai Mountain's Traditional Homes for Ecotourism and Rural Development*, Chunping Xie and Erlin Tian take readers to the ancient tea landscapes of southern China. They argue that the long-term preservation of mountain heritage will increasingly depend on combining indigenous knowledge with modern sustainability standards to ensure resilience, functionality and relevance.

Sarah Balet and Nadja Urfer introduce the concept of regenerative tourism in their article *Regenerative Tourism and its Importance for Conservation Areas and Regional Nature Parks*. They discuss its potential to support both nature conservation and regional development while encouraging a more reciprocal relationship between visitors and destinations.

The Restoration of Aquatic Ecosystems in the Alps and Pyrenees: A Case Study from the LIFE RESQUE ALPYR Project by Teresa Buchaca, Rocco Tiberti, Eulàlia Pladevall-Izard, Lucia Bello, Giorgia Mattioli, Aaron Pérez-Haase, Quim Pou-Rovira, Claudia Rier and Marc Ventura focuses on high-mountain aquatic and semi-aquatic ecosystems in the Alpine biogeographical region. The authors demonstrate how ecological restoration, combined with stakeholder engagement, can contribute to long-term biodiversity gains while reconciling traditional land-use practices with contemporary conservation goals.

Finally, in *Biodiversity in Jiugong Mountain National Nature Reserve, China*, Kang Chen, Yue Teng, Yuhua Xie, Huizhe Feng, Fengge Zhang, Ren Zhu and Kai Zhao provide an overview of the reserve's biodiversity and the pressures it faces. The article discusses threatened species, habitat degradation, invasive species and other conservation challenges, and offers recommendations for improving biodiversity protection in the reserve.

Enjoy exploring this new issue of eco.mont and discovering the new features on the eco.mont website.

Valerie Braun – co-editor of eco.mont

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Potential of use of remote sensing data as additional management tool in Biosphere Reserve networks – a case study of Czech Biosphere Reserves

Petr Cupa & Petr Vahalik

Keywords: Biosphere Reserves, MAB Programme, forest cover, Coefficient of Ecological Stability

Abstract

The main goal of UNESCO's Man and the Biosphere Programme (MAB) is to improve the relationship between people and the environment using biosphere reserves (BR), which can be perceived as comprehensive and collaborative tools for the sustainable management of landscapes and natural resources. The BRs must comprise natural landscapes and examples of the gradation of human environmental impact, allowing for the study and proposal of new approaches to sustainable development. To comply with this agenda, knowledge of the sites' physical characteristics and ecological status is a prerequisite. The availability of public remote sensing data and other readily available sources opens a new approach to periodic BR assessment, even in sites with limited scientific infrastructure. To test and simulate this approach, we spatially joined the BR border polygons with various open-access data sources to analyse the main physical characteristics of six Czech BRs. In the study, we focused on analysing the environmental characteristics of the sites with particular emphasis on the Ecological Stability Coefficient (ESC) as an indicator of conditions needed to improve the ecological stability of the landscapes. The ESC was calculated based on the formula used in the Czech Republic, utilizing the CORINE Land Cover (CLC) dataset. The results showed that five sites have natural and close-to-nature landscapes with a significant predominance of ecologically stable structures and low intensity of human use, and one site has a generally balanced landscape with preserved natural structures. The results suggest that most Czech BRs follow the positive trend in the ESC state, offering feedback to BR coordinators. In addition, the study confirmed sufficient feasibility of open access data (CLC and similar) for temporal assessment of BRs and their ecological stability, which is information required for the periodic review process and as an indicator for the implementation of BR functions. If adjusted to local conditions, the ESC based on the CLC could be considered an additional management tool in mountain biosphere reserves and the rest of the World Network of Biosphere Reserves.

Introduction

Sustainable development is a crucial concept that focuses on the harmonious combination of economic growth, social well-being and environmental protection. Agenda 2030 urged countries to be more active in addressing global challenges through sustainability (UN 2015). There are many ways to seek out strategies to balance sustainable human use and the protection of biodiversity in landscapes managed and used by people (Tobón et al. 2017; Kremen & Merenlender 2018).

One approach is the implementation of the biosphere reserve (BR) concept in landscape management. A key requirement is that each BR must include areas that have different levels of alteration due to human activities. The large-scale protected areas, for example the national parks, are compatible yet different from the BRs (Gregg 1989). While national parks are primarily designated in undisturbed natural areas, BRs encompass human populations as both key contributors and beneficiaries of their activities (Tangley 1988; Price 1996). In terms of national park designation, nature conservation is of the highest priority. At the same time, the BRs must equally fulfill the three main interconnected functions – conservation, development and logistical support for research and education (UNESCO 1996; UNESCO 2017; UNESCO 2022).

Based on their zoning, the BRs are designated so as to find such a balance (Paliwoda et al. 2021). The BR concept has proved its value beyond protected areas and is increasingly embraced by various stakeholders to link biodiversity conservation and socio-economic development for human well-being (Ruoss 2013). The Man and the Biosphere Programme (MAB) requires the inclusion of areas affected by human activities in every BR so as to study the relationship between humans and their environment. One of the first examples of incorporating altered landscape was the Trebonsko (Trebon Basin) BR, partly changed by gravel mining (Jenik 1996). The BRs carry biological and cultural values, history, traditions and heritage, and they focus on using natural resources that people protect and develop. The significant contribution of the BRs to the issue of sustainable development is their ability to cooperate with other similarly oriented networks, e.g. the International Model Forest Network (Cupa & Madera 2019).

As a subject of scientific inquiry, the landscape, not just in BRs, continually prompts questions regarding methodologies and scientific approaches. Being a composite of multiple layers of time and space, the landscape surpasses simplistic, one-dimensional concepts due to its intricate and complex nature (Lapka & Gottlieb 2022). The ecological stability of a landscape is crucial for sustainable development. It involves maintaining and enhancing the resilience of ecosystems to support various life forms while also providing essential services to human societies (Peng et al.

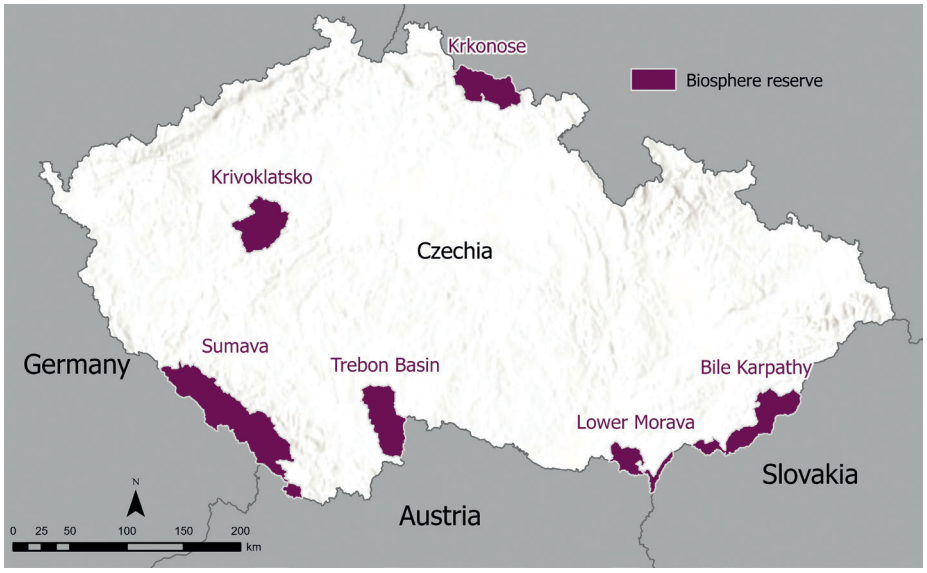


Figure 1 – Location of Czech biosphere reserves. Source: The Nature Conservation Agency of the Czech Republic

2021). A comprehensive understanding and assessment of the anthropogenic impacts on the environment is a prerequisite to maintaining its good ecological state (Vyleta 2019).

An essential component of ecological balance in landscapes is forests that serve as natural shields, mitigating the impacts of increasingly occurring severe weather patterns caused by climate change (Brockerhoff et al. 2017; Sallmannshofer et al. 2023; Moos et al. 2021). That is why we have emphasized the issue of forests as one of the environmental characteristics of the BRs. In addition, many BRs develop strategies to mitigate natural risks. Therefore, ecological stability in BRs is gaining importance in the context of natural disasters or their prevention (Pavlova et al. 2019).

Ecological stability in landscapes is assessed by using various methods to understand an ecosystem's resilience to changes. Diverse approaches can be used to evaluate landscape stability, including calculations of Ecological Stability Coefficients (ESC), soil erosion measurements and similar aspects (Nemetova et al. 2024). The methods must consider the context, management practices and specific landscape studied (Dujka & Kusbach 2023). The results can be used to balance human activities with ecosystem health because there is a strong relationship between landscape stability and land use (Prokopova et al. 2019). Various formulas quantify the ecological stability of landscapes. Specific research was performed by Novakova (1987), Löw (1984; 2003), Michal (1982; 1994), Lipsky

*Table 1 – The area of individual sites, the year of designation, and mountain class. Source: USGS 2025**

Name of the biosphere reserve	Area (ha)	Year of designation	Mountain Class (MC) and Landform Class (LC)
Trebonsko (Trebon Basin)	68,747.7	1977	**K3 LC:** High Hills
Krivoklatsko	62,508.9	1977	**K1 MC:** Elevation = 300 m & Local (7 km radius) Elevation Range > 300 m **K3 MC:** Scattered Low Mountains and Low Mountains
Sumava	16,7586	1990	**K1 MC:** Elevation = 300 m & Local (7 km radius) Elevation Range > 300 m **K3 MC:** Low Mountains
Krkonose	54,969	1992	**K1 MC:** Elevation = 1000 m & Slope >= 5 degrees OR Elevation = 1000 m & Local (7 km radius) Elevation Range > 300 m **K2 MC** **K3 MC:** Low mountains and High Mountains
Bile Karpaty (White Carpathians)	74,701.8	1996	**K1 MC:** Elevation = 300 m & Local (7 km radius) Elevation Range > 300 m **K3 MC:** Scattered Low Mountains and Low Mountains
Dolni Morava (Lower Morava)	34,935.7	2003	**K3 MC:** Scattered Low Mountains and Low Mountains

** USGS Global Mountain Explorer platform works simultaneously with three scientific mountain classifications: K1 by Kapos (2000), K2 by Körner/GMBA (2011), and K3 by Karagulle et al. (2017). K1 is a physical geographic definition based on a combination of elevation, slope, and local elevation range (Kapos et al. 2000). K2 is an ecological classification that defines mountains according to terrain ruggedness and bioclimatic zones, especially the treeline and montane to alpine belts (Körner et al. 2011). K3 is a geomorphological classification using Hammond's landform types, combining slope, relative relief, and surface profile (Karagulle et al. 2017). USGS displays all three layers in parallel because each represents a different scientific perspective on what constitutes a "mountain," enabling comprehensive comparison across physical geography, ecology, and geomorphology.*

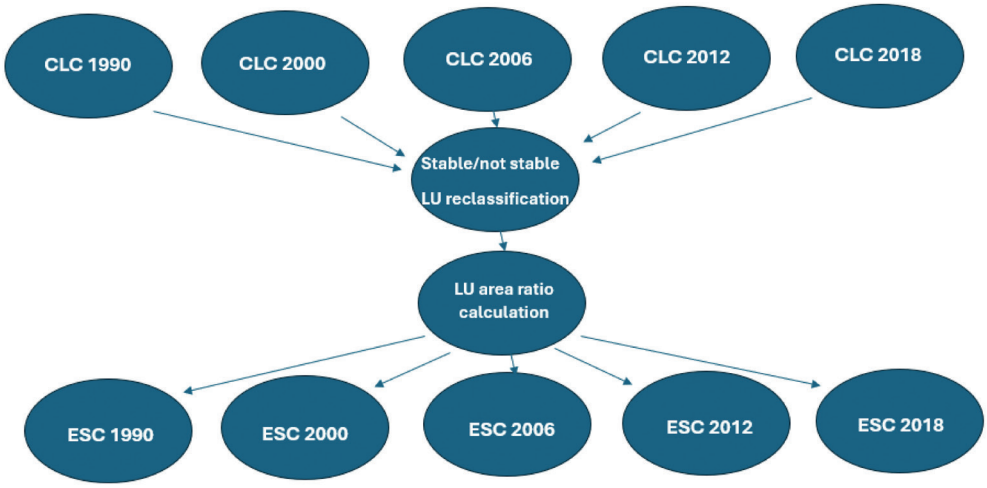


*Figure 2 – A graphic framework model for incorporating the CLC (*CORINE Land Cover*) data and land use (LU) classification into the calculation of the ESC. (Ecological Stability Coefficient)*

(2000) and Rehackova and Pauditsova (2007) in the regions of the Czech Republic and Slovakia. Landscapes are usually very diverse and often contain specific classes that are difficult and frequently impossible to incorporate into one of the habitat quality categories. Therefore, it is crucial to choose a coefficient that considers each element separately with an adequate value assigned (Bazik et al. 2014).

Addressing the issue of human influence on the environment begins with assessing landscape ecological stability, a complex process. This evaluation relies on various mathematical methods, starting with the identification of landscape elements and their classification into predefined categories (Ivan et al. 2014). While these categories may differ across methodologies, they generally share a similar perspective on the eco-stabilization value of landscape elements. The ESC was created and used in the Czech Republic and Slovakia for use in land consolidation (Ivan et al. 2013) or as a part of methodologies and guidelines for documenting territorial ecological stability systems at both regional and local levels, mainly to support state nature and landscape protection initiatives (Húsenicová et al. 1992; Izakovičová et al. 2000). The ESC serves as a key measure for the Czech Statistical Office, the central state administration authority, to assess territorial / landscape stability. It reflects the area's ability to endure external pressures while maintaining its ecological functions (Czech Statistical Office 2024). The ESC evaluates several factors, including landscape composition – the balance between natural and human-made elements within the environment; vegetation cover – the presence of forests, grasslands, water bodies and other natural ecosystems; degree of urbanization – the presence and extent of developed areas and their influence on ecological stability; and environmental resilience – the capacity of the landscape to withstand challenges such as pollution or climate shifts. Additionally, this indicator is used to evaluate environmental carrying capacity. A certain level of ecological stability is a prerequisite for landscape resilience and key principles of environmental sustainability.

Our study introduces a new approach by combining national ESC calculations with the international CORINE Land Cover (CLC) database for broader site assessment. Unlike traditional ESC calculations, which rely on precise but localized data, we prioritized widely accessible datasets that support large-scale analysis, benefiting stakeholders such as BR Coordinators and MAB Programme representatives.

The UNESCO member states must provide the border polygons projected in the WGS84 system (UNESCO 2022) and information about various site attributes (temperatures, precipitation, altitude, endangered species, etc.). Unfortunately, not all BRs have access to relevant site-specific data. Therefore, they are limited to open-access sources. This study aimed to test if the open-access remote sensing datasets, additional public sources and especially the CLC data used in simple ESC calculation can provide sufficient overall temporal assessment of the environmental characteristics that are required for the mandatory periodic review process and that can serve as an additional indicator of BR performance and as a support tool for BR coordinators.

Materials and methods

Study area

This analysis is focused on six Czech BRs that belong to the regional EuroMAB network. The total area of all Czech BRs is 463,449.1 ha, or 5.87 % of the Czech Republic's area (Figure 1).

The first two BRs were designated in 1977. The latest Czech BR was approved in 2003 as an extension of an existing site designated in 1986 (Table 1).

Databases and Methodology

Many BRs worldwide lack adequate scientific infrastructure. Even though this is not the case in the Czech

Republic, to simulate this situation, we used open remotely sensed datasets to obtain primary data complemented by additional data derived from other public sources (e. g. the IUCN Red List), as these sources are available for all UNESCO member states. The software used to extrapolate all data is ArcGIS Pro ver. 3.1.0 (Environmental Systems Research Institute - ESRI). However, QGIS (Open Source Geospatial Foundation Project) can also be used, as it contains the same geoprocessing tools that were used to process the data in this study. The BR border polygons were spatially joined with the following databases for the analysis:

The AW3D (JAXA) World digital terrain model determined the average elevation. The Biogeographical Provinces of the World (Udvardy 1975) were used to analyse the spatial distribution of Czech BRs by biome and province type. The average temperatures are among the characteristics collected from the BRs during the nomination process and periodic reviews. The WorldClim 2 model (Fick & Hijmans 2017) was used for the analysis, offering spatially interpolated monthly climate data at approximately 1 km² resolution. The dataset includes information on temperature (minimum, maximum and average), precipitation, solar radiation, vapour pressure and wind speed. To determine the number of endangered species (excluding birds) in BRs, the IUCN Red List of Threatened Species, Version 2024-1, was used. Currently, the IUCN database's bird section does not allow species selection for the categories of vulnerable, endangered and critically endangered. Therefore, the bird species were excluded from the spatial evaluation. Data on protected areas were sourced from Protected Planet, the World Database on Protected Areas (WDPA) online platform, a collaborative effort between the IUCN and UNEP-WCMC. The Global Forest Change dataset (Hansen et al. 2013) was used to extrapolate forest loss and gain inside the borders of BRs in the period 2000–2020. The CLC dataset, monitoring the pan-European land cover inventory, with an update period of six years, was used to extrapolate the land cover changes within the BRs in the years 1990, 2000, 2006, 2012 and 2018 (Figure 2), providing input for ESC calculations. The updated CLC dataset for 2024 was not yet available when this article was written.

The ESC formula and the interpretation of its results used in the study were designed for the conditions of the Czech Republic. Therefore, there is a limit to potential transferability to the WNBR. In its original form, the group of environmentally stable areas includes forests, hop fields, vineyards, gardens, orchards, permanent grassland, pastures and water bodies. The group of environmentally unstable areas encompasses arable land, built-up areas and other use areas (Czech Statistical Office 2024). These categories do not fully adhere to the structure of CORINE Land Cover layers used as an input. Therefore, we divided the CLC classes into relatively stable and relatively unstable land cover categories (Table 2) based on the assumption that ecological stability is defined as the ability of a given ecosystem to return to its original equilibrium state after disturbance (Ives & Carpenter 2007; Levin et al. 2009) and the intrinsic ability to maintain ecological functions despite disturbance (Turner et al. 1993).

Table 2 – Distribution of CLC and cover classes according to their ecological stability.

Relatively stable areas
Agro-forestry areas
Bare rocks
Beaches, dunes, sands
Broad-leaved forest
Coastal lagoons
Coniferous forest
Estuaries
Fruit trees and berry plantations
Glaciers and perpetual snow
Green urban areas
Inland marshes
Intertidal flats
Land principally occupied by agriculture, with significant areas of natural vegetation
Mixed forest
Moors and heathland
Natural grasslands
Olive groves
Pastures
Peat bogs
Salines
Salt marshes
Sclerophyllous vegetation
Sea and ocean
Sparsely vegetated areas
Relatively unstable areas
Airports
Annual crops associated with permanent crops
Burnt areas
Complex cultivation patterns
Construction sites
Continuous urban fabric
Discontinuous urban fabric
Dump sites
Industrial or commercial units
Mineral extraction sites
Non-irrigated arable land
Permanently irrigated land
Port areas
Rice fields
Road and rail networks and associated land
Sports and leisure facilities

As mentioned above, ecological stability analysis is based on the ESC indicator used by the Czech Statistical Office, one of the state administration authorities, to assess territorial / landscape stability and the environment's carrying capacity (Czech Statistical Office 2024). The ESC formula is defined as the ratio of relatively environmentally stable areas to relatively unstable ones:

$$ESC = \frac{\text{total of relatively stable areas}}{\text{total of relatively unstable areas}}$$

Table 3 – Interpretation of the Ecological Stability Coefficient (ESC).

ESC	Interpretation
< 0.10	territory with maximum disturbance of natural structures; basic ecological functions must be intensively and permanently replaced by technical interventions
0.10 < ESC < 0.30	area with above-average use, with a clear disturbance of natural structures; basic ecological functions must be replaced by technical interventions permanently
0.30 < ESC <1.00	in intensively used areas, mainly by agricultural production, the weakening of self-regulatory processes in ecosystems causes considerable ecological instability and requires high inputs of additional energy
1.00 < ESC < 3.00	a generally balanced landscape in which technical buildings are relatively in harmony with the preserved natural structures, resulting in a lower need for energy and material inputs
> 3.00	natural and close-to-nature landscape with a significant predominance of ecologically stable structures and low intensity of human use of the landscape

The results of ESC calculations are interpreted according to their value (Table 3). ESC is a dimensionless figure. Any value exceeding 3 suggests stable landscapes reflecting an area's high eco-stabilization potential. The weakness of this methodology is that it does not sort into groups the areas with ESC values above 3, even though some can reach a value close to 100 in cases of dominant natural conditions. However, a high ESC is sufficient to gain situational awareness.

Results

Spatial distribution of Czech BRs in the context of protected areas

Five out of six Czech BRs are entirely covered by some form of large-scale protected area (National Park or Protected Landscape Area). Only 13 870.6 ha are located outside protected areas (Table 4), relevant to only one site – the Lower Morava BR.

Biogeographical distribution of Czech BRs

According to the Classification of the Biogeographical Provinces of the World (Udvardy 1975), four of the studied BRs are located in the Mixed Mountain Biome and the Temperate Forest and Woodland Biome (Table 5 and Figure 3).

Main environmental characteristics of Czech biosphere reserves

The terrain of the Czech Republic is very diverse. Two major mountain ranges (the Krkonose Mountains and the Sumava Mountains) and a network of highlands and lowlands shape much of the country's landscape. The Snezka (altitude of 1,602 m asl) – the highest peak in the entire country, is located in the Krkonose BR. The average elevation across the country is about 400 m (World Map Guide 2024). The precipitation and temperature data can provide a valuable baseline for evaluating the changes related to climate change (Table 5). The WorldClim 2 model enables tracking these variations if necessary.

Table 4 – Comparison of protected areas and Biosphere Reserves in the Czech Republic (Source: the authors).

Total area (ha)	7,884,180.00
PA area (ha)	1,732,154.43
PA (%)	21.97
BR area (ha)	461,066.14
BR (%)	5.85
BR area outside PA (ha)	13,870.60

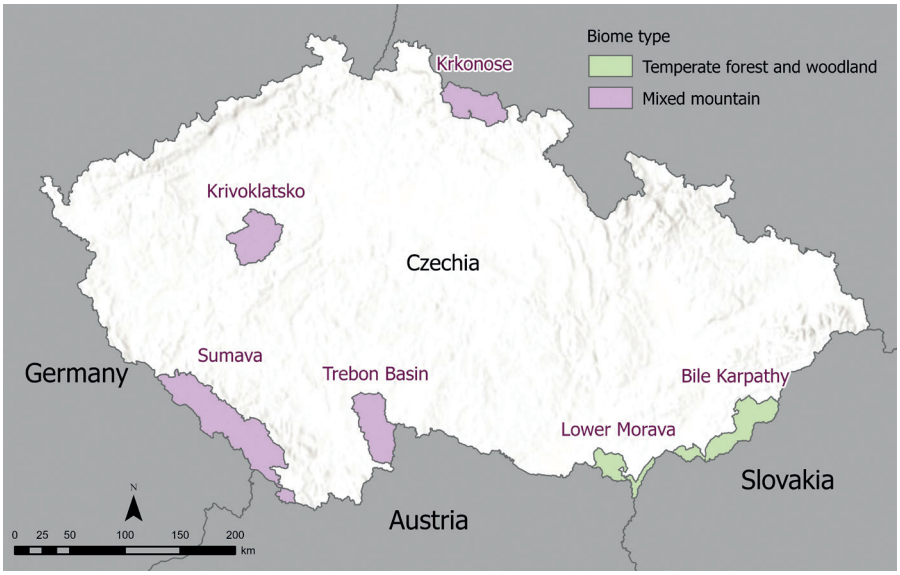


Figure 3 – Spatial distribution of Czech BRs within the biomes (Udvardy 1975).

Table 5 – Biogeographical distribution (Udvardy 1975), number of Vunerable (VU), Endangered (EN) and Critically Endangered (CR) species of the IUCN Red List of Threatened Species (excluding bird species) (IUCN 2024), elevation and temperatures (AW3D and WorldClim 2) and precipitation in Czech BRs (WorldClim 2) in Czech Biosphere Reserves (BR).

BR	Biome type	Number of VU, EN, CR species (IUCN Red List of Threatened Species)	Max. elevation (m asl)	Temperature (°C)			Precipitation (mm)		
				Annual average	Max. in the warmest month	Min. in the coldest month	Annual avg.	Avg. in the driest month	Avg. in the wettest month
Krkonose	Mixed mountain	18	853.1	5.0	18.6	−6.8	689.4	34.8	90.8
Krivoklatsko	Mixed mountain	17	412.1	7.9	22.7	−4.4	597.6	30.7	81.1
Sumava	Mixed mountain	33	905.2	5.6	19.2	−6.0	1163.7	70.1	134.8
Trebonsko	Mixed mountain	20	454.4	7.8	23.0	−4.9	635.0	32.3	88.0
Bile Karpaty	Temperate forest and woodland	26	442.2	7.7	22.8	−5.2	723.7	36.1	97.9
Dolni Morava	Temperate forest and woodland	23	194.0	9.7	25.5	−3.6	598.4	28.6	84.3

The number of vulnerable, endangered and critically endangered species in BRs

In addition to other criteria, the BRs should be significant for biological diversity conservation (Table 5). It must be emphasized that biodiversity cannot be evaluated only by the number of endangered species. Despite that, the MAB collects data on red-listed species. Therefore, we included the analysis of the number of vulnerable (VU), endangered (EN) and critically endangered (CR) species according to the IUCN Red List of Threatened Species (excluding birds) available in the IUCN database.

Forest change in Czech biosphere reserves

Between 2000 and 2022, the forests in some Czech BRs experienced a loss due to various events (Table 6). These events were mainly linked to global climate change and included pests, disease outbreaks or extended periods of drought.

ESC – Ecological Stability Coefficient

The results summarize the development of the ESC in individual BRs between 1990 and 2018. The trend reflects the comparison of the ESC in 2006, when all the sites were already designated, to the situation in 2018, when the latest data originated (Table 7 and Figure 4).

Discussion

Remote sensing data (and other digital databases) are widely used in the evaluation of protected areas, while in the case of BRs, they still need more implementation. Despite that, a similar approach to characterizing ecosystem functioning and functional diversity was implemented, for example, by Cazorla et al. (2023) in the case of the Sierra Nevada BR (Spain), utilizing Ecosystem Functional Type (EFT) classes and their changes and presenting new dataset based on the temporal dynamics of the Enhanced Vegetation Index (EVI) data from the MODIS sensor (MOD13Q1.006). The EFT approach provided insights into conservation priorities, ecosystem reactions to environmental changes and estimating the provision of ecosystem services or model species distribution. This approach is more precise than the one used in this study, requiring more specific data. As many BRs do not have access to specialized datasets, we tried to work with open sources to obtain information usable for assessing and providing situational awareness within the World Network of BRs (WNBR).

The ESC calculation for temporal BR evaluation seems more frequent and was applied, for example, by Olah and Boltižiar (2009) in the case of four Slovak BRs. They used a different formula, $ESC = (\sum pi.ki)*p^{-1}$, where pi is an area of land use form; ki is the ecological significance of land use

Table 6 – Forest loss and gain in Czech BRs (Global Forest Watch – Copernicus).

BR	Forest loss 2000–2022		Forest gain 2000–2012		Forest loss 2000–2012	
	ha	% of BR area	ha	% of BR area	ha	% of BR area
Bile Karpaty	3,701.9	5.0	923.5	1.2	1,493.9	2.0
Krivoklatsko	3,959.3	6.3	1,144.2	1.8	1,634.1	2.6
Krkonose	2,780.7	5.1	3,181.1	5.8	924.5	1.7
Dolni Morava	1,967.9	5.6	351.2	1.0	1,183.5	3.4
Sumava	17,603.1	10.5	4,095.6	2.4	11,384.5	6.8
Trebonsko	4,047.2	5.9	1,545.5	2.2	1,939.7	2.8

Note: The data are based on a 12-year period (2000–2012) due to the limited availability of extrapolated forest growth data derived from satellite imagery. Forest increment data are available for that period because a forest needs a certain period of growth (more than 10 years) to be analysable from satellite data. This contrasts with forest loss, which is visible immediately and can be analysed continuously.

Table 7 – Ecological Stability Coefficient (ESC) according to CORINE Land Cover classes (+ positive trend, – negative trend).

Biosphere Reserve name	Year of designation	ESC					Trend 2006–2018
		1990	2000	2006	2012	2018	
Bile Karpaty	1996	2,05961	3,21316	4,09125	4,54818	4,51856	+
Krivoklatsko	1977	2,53394	2,94699	3,06936	3,43299	3,42624	+
Krkonose	1992	8,63252	24,4112	24,8815	18,1074	17,728	–
Dolni Morava	2003	1,19481	1,28032	1,41765	1,48262	1,52481	+
Sumava	1990	14,5937	66,1693	74,3012	94,7681	95,5761	+
Trebonsko	1977	2,47493	3,43419	3,57178	4,4188	4,47866	+

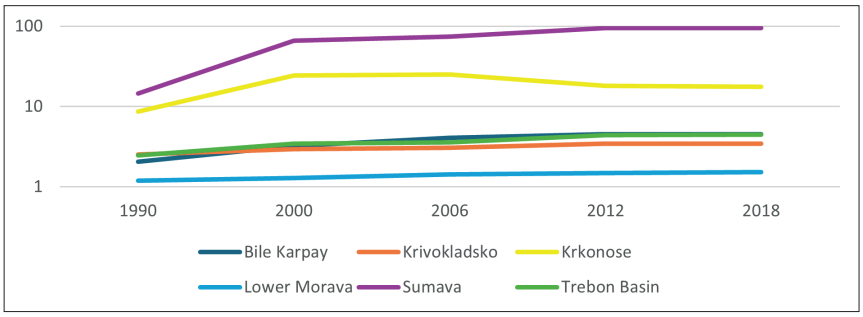


Figure 4 – Trend in the evolution of Ecological Stability Coefficient values in landscapes of Czech Biosphere Reserves between 1990–2018.

form; and p is the total area (Miklos 1986). The input data was based on conventional historical and current maps and aerial orthophotographs processed in GIS. The results were more accurate than our study but required more detailed input data. Despite different methods, ESC calculation was validated as an instrument for assessing BRs, which our study confirmed. In any case, it should not imply that the low-scoring BRs have inappropriate management, and the high-scoring sites have immaculate management, as more precise data are always needed for responsible evaluation. An on-site survey must verify the indicated problems. For example, the negative trend in the development of ESC in the Krkonose BR, presented in this study, was caused by a combination of planned timber harvest, mugo pine (*Pinus mugo*) control measures to mitigate inappropriate planting in the past and mainly necessary forestry measures called for by bark beetle (Ips typographus) outbreak. However, despite the trend, the local survey confirmed that the site maintains a very high ESC status and that all the implemented measures are closely monitored and reviewed.

Alternative indicators of stability, such as the Normalized Difference Vegetation Index (NDVI) or Land Use / Land Cover (LULC) changes, have been considered. However, their effect is significantly influenced by local aspects. NDVI changes are strongly affected by regional climate, and LULC varies in the importance of habitat types in the local context. Modern technologies in remote sensing such as the Sentinel satellite system, LIDAR, machine learning and AI-based classification, or multispectral images with very high resolution such as WorldView III , World View Legion, SkySat and others as well as analysis of radar satellite data are providing very accurate assessments of environmental aspects or indicators of ecological stability at the local level. However, adopting these technologies for a global methodological procedure brings high demands to the processing team, which is often not within the capabilities of BR management. Such a sophisticated approach will also necessarily introduce high variability in the interpretation of the outputs, resulting in their mutual incomparability.

Generally, the use of remote sensing data in larger sections of the WNBR may bring several challenges. One is related to the need for more current data on borders in digital form in BRs in less developed countries. This issue is currently being resolved through the generation of the UNESCO Biodiversity Portal. Another issue may involve the need for more information to be provided by the states to the CLC datasets. Another area for consideration is that there needs to be a universal methodology to assess the stability of land uses according to their influence on the ecological stability of the landscapes. A topic for future discussion is remote sensing data sources, an alternative to CLC, which are utilized in various parts of the world. Additional challenges stem from the technical limits of the CLC. For example, there is the issue of the generalization of data used by the CLC. The CLC implements images provided by Landsat with 30 m pixels. Should the ESC be used as a precise indicator of BR performance or as a tool for the BR managers to improve decision-making? More accurate databases based on orthophotos or images acquired by unmanned aerial vehicles must be employed. Regarding not only BRs, the ecological stability of landscapes is fundamental to balancing human needs and the environment's capacity to provide resources and services sustainably. The more information is available, the higher the quality of the landscape management measures implemented, and the actions proposed.

The article is not primarily focused on suggesting practical measures for improved decision-making by BR managers. Our work aims, above all, to highlight the use of the ESC based on the CLC as a tool to identify potentially problematic areas and initiate remediation processes if necessary. The practical applications must be completed individually, and the experience gained can be a topic for additional studies.

Despite its limitations, the ESC, in its current form, can be used to support management decisions regarding human activities within BRs. In terms of BRs, the majority of human activities occur in the transition area, partly in the buffer zones and seldom in core areas. A negative trend in ESC may signal potential problems, and subsequent analysis of input data can help explain which unstable areas are increasing in size and why. The proposed follow-up management decisions can be more targeted in terms of measures to be taken and stakeholders with whom to cooperate.

Conclusion

Protected areas overlap with five out of six Czech BRs entirely. The reason is that they were designated before the Seville Strategy for BRs (UNESCO 1996), which clearly distinguished BRs from protected areas, was fully adopted. This situation is different from the present trend in BR designation. Currently, the BRs within the majority of the respective UNESCO member states do not entirely coincide with protected areas, which is perceived as positively affecting the ability of the sites to fulfill their main functions equally, as well as the aptitude of governance structures to be more inclusive in terms of stakeholder participation. In addition, the territorial extension outside protected areas contributes to a better public understanding of the BR concept and improved differentiation from protected areas.

According to our analysis, the Czech BRs' composition meets the MAB criteria in terms of including diverse biomes and ecosystems, significance for biodiversity and potential for exploring approaches to sustainable management of natural resources in various conditions. These prerequisites are based on the requirements prescribed by the Statutory Framework for BRs. The question is whether the new challenges caused, for example, by global climate change can be currently fully addressed or whether new criteria are needed for establishing and transforming BRs, encompassing natural and human relationships and values as proposed by Stoll-Kleemann and O'Riordan (2018).

Our study introduces a novel approach by integrating national ESC calculations with the international CLC database for comprehensive site assessment. Traditionally, ESC calculations rely on alternative base data, which, while potentially more precise, are often localized and unsuitable for broader applications, such as BR networks. To enable large-scale assessments, we opted for datasets that encompass extensive areas and are widely accessible – ensuring broader usability for various stakeholders, including BR Coordinators and representatives of national and international MAB Programmes – and that have been tested on Czech BRs.

The reliability or accuracy of the ESC indicator depends on the data source. The ESC assessment in this study was based on calculations that work with rather general datasets of the CLC. Therefore, the results can provide only a comprehensive overview of individual sites and the MAB networks if used on a larger scale. In the Czech Republic, where the ESC is widely used, the Czech Statistical Office produces the input data with only medium accuracy. The data is derived from the land types listed in the Land Register, which has limited accuracy. If there is a GIS register of land available, then the calculations of the ESC are relatively accurate. However, our approach can be used for preliminary surveys to identify areas where the issue of ecological stability might need special attention.

A positive feature of CLC use is the repeatability of the study, which results from regular updates of the CLC every six years. Periodic updates can facilitate long-term observations of changes, and the iteration can be reflected in the compulsory BR Periodic Review process, with a 10-year update period

The ESC calculations have limitations in data availability, essential variables and land cover classes. Despite that, the BR coordinators can use the basic ESC calculation to manage and plan sustainable development measures if the variables and input data are adjusted to local conditions. General characteristics and calculated ESC suggest that all Czech BRs have favorable conditions for maintaining or improving ecological stability. Five Czech BRs have natural and close-to-nature landscapes with a significant predominance of ecologically stable structures and low intensity of human use. One site has a generally balanced landscape with preserved natural structures.

The forest cover changes signal the need for additional research as five Czech BRs experienced more significant forest loss than forest gain between 2000 and 2012. As the BRs are perceived as *living laboratories of sustainable development*, their forests offer unique opportunities for transforming new information into recommendations for forest management measures (Madera et al. 2011). The analysis of forest loss and gain can be used as an indicator by the BR coordinators to adapt specific forest management measures, including expedited reforestation.

The analysis of information about the essential characteristics of Czech BRs using the remote sensing data can indicate a possible approach to raising situational awareness on a larger scale as a basis for creating common strategies at the BR networks and improving networking between the BRs. The analysis can add to sound decision-making in BR management and upgrade MAB Programme coordination, even without using special access databases. In addition, the analysis results can provide new momentum for generating

topics for applied research, where every BR can be a platform for scientists to work together with practitioners. Other fields that might benefit include sustainable economic activities like agriculture, forestry and tourism without degrading the environment; climate change mitigation through carbon sequestration; and urban planning promoting green infrastructure or the prevention of the impacts of natural disasters by planning natural barriers against floods, landslides and other hazards.

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The Carbon Sequestration Potential of the Dibudalan Mountain Forest Reserve, Philippines

Afed Daiwey

Keywords: endemic trees, species diversity, above-ground biomass, carbon sequestration, Dibudalan Forest

Abstract

The Dibudalan Mountain Forest Reserve (DMFR) in Aurora, Philippines, is a tropical secondary forest characterized by a varied tree species and considerable carbon sequestration potential. Using 13 permanent quadrats along two belt transects, tree composition, biomass and carbon stock were assessed. A Shannon–Wiener diversity index of 3.543 was calculated from a total sampling population of 444 trees representing 57 species and 31 families, indicating a highly diverse forest status of the study area. A large amount of sequestered carbon that substantially contributed to the above-ground biomass was collectively concentrated in a few trees with large-diameter trunks, particularly *Lagerstroemia piriformis*, *Xanthostemon philippinensis*, *Wrightia pubescens*, and *Artocarpus odoratissimus*. The notable total carbon stock across quadrats, averaging 250.95 tC/ha reflects the stand's different structure and disturbance history. The ecological importance of the DMFR highlights the dominance of endemic and vulnerable species. Results underscore the need to implement forest management strategies that enhance the protection of high-biomass trees while sustaining biodiversity, safeguarding ongoing carbon sequestration and promoting ecosystem resilience.

Profile

Protected area

Dibudalan Mountain Forest Reserve

Country

Philippines

Introduction

Forests are more than just a collection of trees, they are the world's most significant carbon sink because of their exceptional ability to absorb carbon from the atmosphere. However, the efficiency of sequestration depends on the structure, composition and biomass of the tree communities they harbour.

The Dibudalan Mountain Forest Reserve (DMFR) lies along the central–eastern section of the Sierra Madre Mountain Range in the Philippines and represents a distinctive forest ecosystem composed of diverse tree species uniquely adapted to ultramafic soils. This rare ecological system of the DMFR supports high biodiversity but remains highly sensitive to disturbance. In previous years, the increasing anthropogenic activities associated with the development of school site reservations began threatening the fragile balance of this mountain due to land-use changes.

Although carbon sequestration in tropical forests has been widely studied at both global and regional scales (Bhatia 2014; Keith et al. 2009; Fennessy & Beers 2023; Fedrigo et al. 2014), the information on carbon sequestration in the ultramafic mountain forests of Dibudalan remains scarce. This lack of data constrains the understanding of how Dibudalan Forest contributes to climate change mitigation, sustainable biodiversity conservation and sustainable forest management. Thus, addressing this knowledge gap is essential, particularly for quantifying the forest's potential carbon stock. Accordingly, this study aims to examine tree species and their taxonomic composition, richness and abundance; estimate above-ground biomass; determine carbon stored per quadrat; and assess the current conservation and endemism status of the forest. Field data were scientifically collected from the systematically established quadrats along modified transect belts. Trees with a Diameter at Breast Height (DBH) of 5 cm and above were measured, and biomass was estimated using locally developed allometric equations. A total of 444 sampling trees representing 57 species across 31 families were recorded with a Shannon index of 3.543, demonstrating a highly significant level of species diversity in the province.

A small number of mature species, such as *Lagerstroemia piriformis*, *Xanthostemon philippinensis* and *Wrightia pubescens*, contributed disproportionately to the total carbon stock of 250.95 tC / ha. In contrast, smaller species, though contributing less to biomass, were crucial for sustaining species richness, forest structures and resilience. The conservation assessment revealed a remarkable prevalence of endemic species (70.27%), underscoring the ecological significance of the DMFR and the urgency of coherent forest management.

In general, the study provides a comprehensive baseline for sustainable forest management by bringing together all the information on species composition, potential biomass stocks and conservation status. The findings led us to a vibrant conservation plan for the DMFR's continued service as a climate regulator and biodiversity protector.

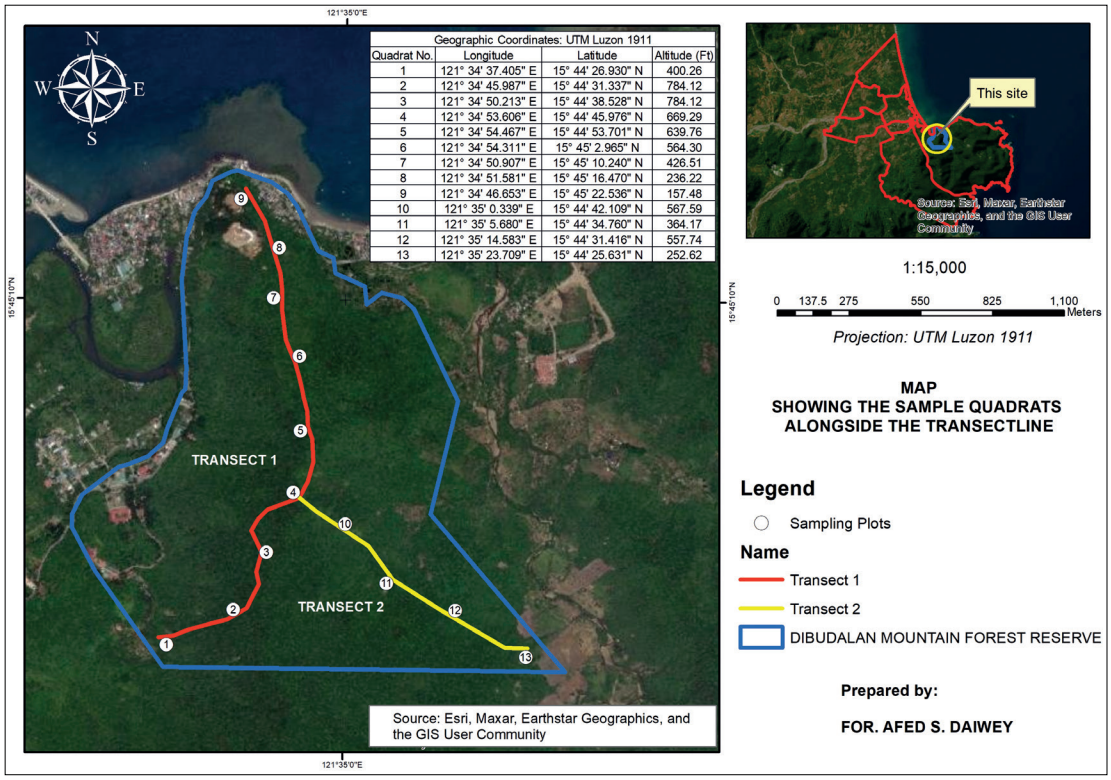


Figure 1 – Map overview of the Dibudalan Mountain Forest Reserve.

Methodology

Study site

The study was located at the Dibudalan Mountain Forest Reserve (DMFR), proclaimed under Proclamation No. 87, s. 1966 and declared as the school site civil reservation of the Aurora State College of Technology (ASCOT) through Proclamation No. 559, s. 1995 (Figure 1). The DMFR is geographically situated in the municipality of Baler, Aurora Province (Daiwey et al. 2024), which is historically known as the birthplace of President Manuel L. Quezon and the last Spanish garrison in the Philippines (Angara 2007). The DMFR lies along the Sierra Madre Mountain Range (SMMR), one of the world's ecologically vital regions, encompassing the nine eastern provinces of Luzon from Cagayan to Quezon (Ploeg et al. 2003). Dibudalan Forest supports diverse floristic species that play crucial roles in carbon sequestration, maintaining ecological stability and protecting habitat integrity. However, since its classification as a school site reservation, the DMFR has been under public pressure to facilitate the construction of ASCOT infrastructures and other human needs (Angara 2022). Such land-use change altered the forest structure, reduced potential biomass stocks and jeopardized the forest's long-term capacity to act as a carbon sink. This event drove the author to initiate this study to determine the current carbon stock of the DMFR and as a response also to the global demand of the World Health Organization (WHO) to all countries, through the United Nations Framework Convention on Climate Change (UNFCCC), to assess their contributions to carbon offset and evaluate approaches that control carbon dioxide accumulation in the atmosphere.

Data gathering and assessment

Two modified belt-transect lines and 13 quadrats were established as baseline plots for tree identification and estimation of the carbon sequestered. The first transect (T1) measured 2,000 m in length, while the second transect (T2) measured 1,000 m long. T2 is shorter than T1 because of the narrower configuration in the southern portion of the study area. T2 was added to ensure a representative sampling distribution within the forest reservation.

The first transect has 9 quadrats established at the very start of the transect line, with grid coordinates of 121°34'37.405"E and 15°44'26.930"N. The remaining quadrats of T1 were systematically distributed at 250 m intervals up to its endpoint. T2 has only 4 quadrats started at Quadrat 10, with grid coordinates of 121°35'0.339"E and 15°44'42.109"N, and then followed by the rest.

The 20 m x 20 m plot sample size and 250 m intervals applied in the study were adapted from the standard manual and guidelines on biodiversity assessment (DAO-BMB 2024), as this plot size provides the best balance in assessing tree species diversity and biomass in the tropical forest ecosystem of the Philippines.

The transects followed the existing trails for the purposes of convenience. However, the quadrats were placed at least 3 m away from the trails to minimize potential bias, as the trails were characterized by open

space resulting from soil compaction, disturbed vegetation and altered species distribution caused by human activities and animal movement. Placing the quadrats slightly away from these disturbances ensured more accurate data collection that reflects the natural conditions of the DMFR. This approach enhanced the study's reliability by providing a more precise assessment of carbon stocks free from trail-related factors. The established quadrats served as permanent monitoring stations for assessing and revalidating the existing tree assets and woody vegetation of the DMFR (Obemio et al. 2016).

Throughout the evaluation, a portable Global Positioning System (GPS) receiver was used to obtain the coordinates of each quadrat. Subsequently, the classification of trees within each quadrat was scientifically identified and revalidated. The circumference of the observed trees was measured using a tape measure and converted to diameter by dividing it by π (3.1416) a conventional conversion factor. The diameters of each species were summed to obtain cumulative values that represent the sum of individual measurements across all sampling units. This cumulative diameter will serve as a multiplier to calculate the carbon sequestered.

However, measurements were limited to trees with a DBH of ≥5 cm measured at 1.3 m above ground level. This method follows the forestry and biodiversity assessment standard protocols (Chave et al. 2005). Trees with a DBH of <5 cm were excluded due to their high mortality rates and negligible contribution to forest biomass and structure. Trees with unique morphological features were assessed following the framework developed by Husch et al. (2003). Likewise, the expertise of a dendrologist is vital in revalidating trees with uncertain identities before carbon stock calculation.

The authenticity of taxonomic classification, conservation status and endemism of identified flora was evaluated by comparing them in the existing online databases of the International Union for Conservation of Nature Red List of Threatened Species (IUCN 2023), the updated national list of threatened Philippine plants (DAO 2017) and the Philippine digital flora database of Leonardo L. Co. (Pelser et al. 2011).

Data Analysis

Species richness and abundance were analysed using field-collected data. Species richness was determined by counting the number of species within each quadrat, while abundance was measured by the number of individual trees per species found within the same area. On the other hand, the species diversity was interpreted and calculated following the Shannon-Weiner diversity index formula utilized by Chetry et al. (2025), wherein:

$$H' = -\sum_{i=1}^{s} Pi \ln Pi$$

H' = Shannon-Weiner diversity index
$\sum$ = summation over all species in the country
Pi = proportion of individuals belonging to i
ln = natural logarithm

The following formula was adapted according to Dave et al. (2025)

$$pi = ni / N$$

n_i = number of individuals of species i
N = total number of individuals of all species

Interpretation reminder of H':
<1.0: Low diversity
1.0 – 3.0: Moderate diversity
> 3.0: High diversity

In the calculation of carbon sequestration, a series of local allometric equations using the DBH of various tree species as a reference was employed. The first step is to calculate the potential Above Ground Biomass (AGB) using the equation developed by Banaticla et al. (2007). The formula applied is

$$Y\ (kg) = 0.342\ (dbh)^{2.073}$$

Y = the above-ground biomass in kg.
dbh = the measured diameter at 1.3 m above the ground in cm.

The second step is the calculation of carbon stock using the foundational empirical basis equation by Brown (1997), which was adapted and developed in the Philippines by Lasco and Pulhin (2003) after supporting the national use of 0.45 for Philippine tropical forest conditions. The formula applied is

$$C\ (kg) = AGB * 45\%$$

C = carbon stock
AGB = computed above-ground tree biomass
45% = carbon content of tree biomass

The 45% figure indicates that the tree contains 0.45 kg of carbon per 1 kg of dry biomass. The kilogram (kg) unit was converted to tons of carbon per hectare (tC / ha) by dividing the computed carbon value by 1,000 a common conversion factor in the country. This proportion is commonly employed in carbon stock assessments of tropical forests of the Philippines. Further, the Intergovernmental Panel on Climate Change (IPCC 2006) standards allow a 47% tolerance for tropical forests' Carbon Fraction (CF) values. However, the Philippines is prepared to employ 45% because local researchers discovered that the average carbon content of tropical hardwoods is about 43%–47%, not 50% (Lasco & Pulhin 2003).

Table 1 – Tree species composition, relative proportion (pi) and Shannon–Wiener diversity index (H') values of trees in the DMFR.

No.	Species	Family	Population (ni)	pi	ln(pi)	−pi ln(pi)	Status
1	*Mangifera altissima* Blanco	Anacardiaceae	16	0.036	−3.323	0.120	NT
2	*Mangifera indica* L.	Anacardiaceae	1	0.002	−6.096	0.014	LC
3	*Xylopia brasiliensis* Spreng.	Annonaceae	3	0.007	−4.997	0.034	U
4	*Alstonia macrophylla* Wall. ex G.Don	Apocynaceae	6	0.014	−4.304	0.058	U
5	*Vitex* spp.	Apocynaceae	4	0.009	−4.710	0.042	U
6	*Ilex cumingiana* Rolfe	Aquifoliaceae	5	0.011	−4.486	0.051	U
7	*Celtis philippensis* Blanco	Araliaceae	8	0.018	−4.016	0.072	U
8	*Acanthophoenix rubra* (Bory) H.Wendl.	Arecaceae	1	0.002	−6.096	0.014	U
9	*Cordyline australis* (G.Forst.) Endl.	Asparagaceae	4	0.009	−4.710	0.042	LC
10	*Canarium odontophyllum* Miq.	Burseraceae	3	0.007	−4.997	0.034	T
11	*Celtis paniculata* (Endl.) Planch.	Cannabaceae	1	0.002	−6.096	0.014	U
12	*Tristaniopsis decorticata* (Merr.)	Cannabaceae	1	0.002	−6.096	0.014	U
13	*Casuarina equisetifolia* L.	Casuarinaceae	2	0.005	−5.403	0.024	LC
14	*Gmelina arborea* Roxb. ex Sm.	Clusiaceae	7	0.016	−4.150	0.065	LC
15	*Syzygium simile* (Merr.) Merr.	Combretaceae	17	0.038	−3.263	0.125	DD
16	*Dillenia luzoniensis* Merr.	Dilleniaceae	2	0.005	−5.403	0.024	CE
17	*Hopea philippinensis* Dyer	Dipterocarpaceae	1	0.002	−6.096	0.014	E
18	*Parashorea malaanonan* (Blanco) Merr.	Dipterocarpaceae	7	0.016	−4.150	0.065	V
19	*Pterocarpus rotundifolius*	Dipterocarpaceae	1	0.002	−6.096	0.014	U
20	*Shorea gisok* Foxw.	Dipterocarpaceae	11	0.025	−3.698	0.092	E
21	*Lagerstroemia speciosa* (L.) Pers.	Euphorbiaceae	8	0.018	−4.016	0.072	LC
22	*Macaranga grandifolia* (Blanco) Merr.	Euphorbiaceae	2	0.005	−5.403	0.024	U
23	*Afzelia rhomboidea* Fern.–Vill.	Fabaceae	2	0.005	−5.403	0.024	V
24	*Beilschmiedia tawa* (A.Cunn.) Kirk	Fabaceae	1	0.002	−6.096	0.014	U
25	*Polyscias nodosa* (Blume) Seem.	Fabaceae	1	0.002	−6.096	0.014	U
26	*Lithocarpus solerianus* (Vidal) Rehder	Fabaceae	8	0.018	−4.016	0.072	U
27	*Anthocleista grandiflora* Gilg	Gentianaceae	6	0.014	−4.304	0.058	U
28	*Calophyllum obliquinervium* Merr.	Guttiferae	1	0.002	−6.096	0.014	U
29	*Cratoxylum sumatranum* (Jack) Blume	Hypericaceae	2	0.005	−5.403	0.024	U
30	*Lagerstroemia piriformis* Blume	Lythraceae	33**	0.074	−2.599	0.193	U
31	*Shorea polysperma*	Malvaceae	12	0.027	−3.611	0.098	E
32	*Sterculia foetida* L.	Malvaceae	2	0.005	−5.403	0.024	LC
33	*Artocarpus blancoi* (Elmer) Merr.	Meliaceae	22****	0.050	−3.005	0.149	V
34	*Artocarpus odoratissimus* Blanco	Meliaceae	51*	0.115	−2.164	0.249	LC
35	*Dysoxylum alliaceum* (Blume) Blume.	Meliaceae	10	0.023	−3.793	0.085	U
36	*Ficus ampelos* Burm.f.	Meliaceae	3	0.007	−4.997	0.034	U
37	*Ficus variegata* Blume	Meliaceae	12	0.027	−3.611	0.098	LC
38	*Pterocarpus indicus* Willd.	Meliaceae	5	0.011	−4.486	0.051	V
39	*Sterculia rubiginosa* Vent.	Meliaceae	5	0.011	−4.486	0.051	U
40	*Ficus balete* Merr.	Moraceae	1	0.002	−6.096	0.014	U
41	*Myristica philippensis* Lam.	Myristicaceae	3	0.007	−4.997	0.034	V
42	*Acacia auriculiformis* A.Cunn. ex Benth.	Myrtaceae	2	0.005	−5.403	0.024	LC
43	*Swietenia macrophylla* King	Myrtaceae	16	0.036	−3.323	0.120	LC
44	*Syzygium garciae* (Merr.) Merr.	Myrtaceae	8	0.018	−4.016	0.072	U
45	*Syzygium leucoxylon* Korth.	Myrtaceae	26***	0.059	−2.838	0.166	LC
46	*Terminalia catappa* L.	Myrtaceae	1	0.002	−6.096	0.014	LC
47	*Wrightia pubescens* (Blanco) Ngan	Myrtaceae	6	0.014	−4.304	0.058	U
48	*Xanthostemon philippinensis* Merr.	Myrtaceae	20*****	0.045	−3.100	0.140	E
49	*Pandanus exaltatus*	Pandanaceae	12	0.027	−3.611	0.098	U
50	*Drypetes grandifolia* (C.B.Rob.)	Putranjivaceae	14	0.032	−3.457	0.109	U
51	*Hypobathrum racemosum* (Roxb.)	Rubiaceae	9	0.020	−3.899	0.079	U
52	*Morinda citrifolia* L.	Rubiaceae	2	0.005	−5.403	0.024	LC
53	*Melicope vieillardii* (Baill.) Guillaumin	Rutaceae	1	0.002	−6.096	0.014	U
54	*Palaquium dubardii* Elmer	Sapotaceae	3	0.007	−4.997	0.034	V
55	*Palaquium luzoniense* (Fern–Vill.) Vidal	Sapotaceae	5	0.011	−4.486	0.051	V
56	*Palaquium merrillii* Dubard	Sapotaceae	19	0.043	−3.151	0.135	V
57	*Prasoxylon alliaceum* (Blume) M.Roem.	Verbenaceae	9	0.020	−3.899	0.079	U
	TOTAL	31	444				
	Shannon Diversity Index (H')					3.543	

,,***,**** and***** = Top 5 species with highest population and diversity index*
U=unknown, LC=Least Concern, V=Vulnerable, E=endangered, DD=data deficit, NT=near threatened, T=threatened, CE=critically endangered.
ni=number of individuals of species
pi (π) = proportional abundance of species i in the community. It is calculated as pi = ni/N, where ni is the number of individuals of that species (e.g. 16 for Mangifera altissima), and N is the total number of individuals across all species which is 444. In the table, pi = 0.036 means that this species makes up about 3.6% of the total population.
ln(pi) = natural logarithm (base e) of pi. This transforms the proportion into a logarithmic scale, which is used to measure evenness or rarity in diversity calculations. In the table, ln(pi) = -3.323, indicating that this is a relatively rare species (negative value since pi < 1).
-pi ln(pi) = negative product of pi and ln(pi) and represents each species' contribution to the overall Shannon diversity index. This term penalizes uneven distributions (e.g., dominant vs. rare species). In the table, -pi ln(pi) = 0.120, a small value suggesting a low contribution from this rare species.

Table 2 – Composition, relative abundance and contribution to Shannon–Wiener diversity of tree species in the DMFR.

Abundance Category	Population Class (ni)	Richness (Community)	Evenness
Low	1–5	31	0.32
Moderate	6–19	17	0.6
High	≥ 20	9	0.88

Given that the study was conducted locally, the author used the local allometric equations published by Banaticla et al. (2007) and Lasco and Pulhin (2003) in estimating the above-ground biomass and carbon stocks of the DMFR, as the empirical data were collected in the Philippines. This equation is suitable to use as it provides greater accuracy and relevance than the Asian setting used by Pragasan (2022) and other global models, which may not reflect the local growth conditions of tree species in the Philippines. These equations enhance the credibility of the DMFR's carbon stock estimates, which align with national forestry research standards and provide reliable data for ecological assessment and carbon accounting in Philippine forests.

Results

Tree inventory assessment

Table 1 shows the species taxonomic composition, relative abundance and parameters used in calculating the Shannon–Wiener diversity index (H') of trees inventoried in the 13 sampling quadrats established in the Dibudalan Mountain Forest Reserve. A total of 444 individual trees, representing 57 species from 31 families were recorded. The five most abundant species (marked with asterisks) registered the highest relative abundance values and the most significant numerical contributions to H'.

The total Shannon-Wiener diversity index was computed as 3.543. This H' index was calculated based on the proportional contributions of each species, from low to high relative abundance, in the sample plots.

Table 2 presents the composition, relative abundance and contribution to Shannon–Wiener diversity of tree species in the DMFR. As the number of tree species in the DMFR increased, so did the evenness of the species. Species with low abundance (1–5 individuals) exhibited low evenness (E = 0.32), while possessing the maximum species richness (31 species), suggesting an unequal distribution of individuals across several rare species. Moderate-abundance species (6–19 individuals) exhibited moderate evenness (E = 0.60), but extremely abundant species (≥ 20 individuals) showed high evenness (E = 0.88), indicating a more equitable distribution of individuals among a limited number of dominating species.

Baseline carbon sequestration

Table 3 presents the estimated value of above-ground biomass (AGB) and carbon stock based on DBH measurements. A total of 57 tree species were examined, and each showed significant variation in both AGB and carbon storage. The total carbon stock of all sampled trees is 250.949 tC / ha.

The five tree species with the highest cumulative carbon stock that collectively contribute to the total carbon stock are *Lagerstroemia piriformis* (57.931 tC / ha), *Xanthostemon philippinensis* (45.473 tC / ha), *Wrightia pubescens* (32.362 tC / ha), *Artocarpus odoratissimus* (29.402 tC / ha) and *Palaquium merrillii* (12.386 tC / ha). These plants typically have bigger DBH, which was used to measure carbon stock.

On the other hand, trees with the lowest carbon stock contribution were *Pandanus exaltatus* (0.004 tC / ha), *Pterocarpus indicus* (0.006 tC / ha), *Morinda citrifolia* (0.015 tC / ha), *Tristaniopsis decorticata* (0.015 tC / ha) and *Mangifera indica* (0.017 tC / ha). These types of trees are characterized by smaller DBH, resulting in lower biomass accumulation.

The data show a positive relationship between tree size (DBH) and carbon stock, wherein the largest trees contribute most to the forest's carbon pool. A strong positive relationship means that large-diameter trees contribute disproportionately to the total forest carbon stocks and serve as the primary reservoirs of carbon within the forest ecosystem. This observation on the positive relationship between DBH and carbon stock aligns with the study results of Hasan et al. (2025), who argued that carbon stock increases as DBH increases. Whereas medium-sized trees, such as *Casuarina equisetifolia* (0.222 tC / ha), *Gmelina arborea* (0.365 tC / ha) and *Swietenia macrophylla* (0.197 tC / ha), contributed moderately to the total carbon stored, species with smaller DBH contributed little to the total carbon volume.

Total carbon stock varied considerably across the 13 quadrats (Figure 2), ranging from 3.67 to 78.39 tC / ha. Quadrats 2, 4 and 3 recorded the highest carbon stocks, with values of (78.39 tC / ha), (70.30 tC / ha) and (59.14 tC / ha) respectively. Moderate carbon stocks were observed in Quadrats 1, 5, 6, 7, 8 and 9, ranging from 25.32 to 54.28 tC / ha. In contrast, Quadrats 10 to 13 exhibited notably low carbon stocks, averaging only ≤ 6 tC / ha, indicating

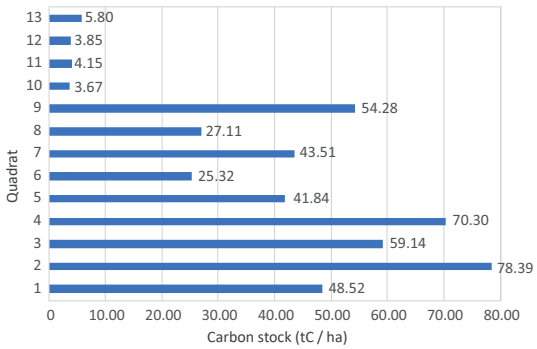


Figure 2 – Total carbon stock (tC / ha) recorded per quadrat in the study area.

Table 3 – Carbon stocks and Above-ground Biomass (AGB) Estimates of tree species based on DBH (diameter at breast height) measurements.

Species	DBH	AGB (kg/sp.)	Carbon Stock (kg)	Carbon Stock (tC/ha)
Acacia auriculiformis A.Cunn. ex Benth.	11.94	58.398	26.279	0.026
Acanthophoenix rubra (Bory) H.Wendl.	10.5	44.803	20.162	0.020
Afzelia rhomboidea Fern.-Vill.	38.2	650.991	292.946	0.293
Alstonia macrophylla Wall. ex G.Don	21.49	197.505	88.877	0.089
Anthocleista grandiflora Gilg	21.49	197.505	88.877	0.089
Artocarpus blancoi (Elmer) Merr.	179.05	16,011.658	7,205.246	7.205
Artocarpus odoratissimus Blanco	352.85	65,338.538	29,402.342	29.402 v
Beilschmiedia tawa (A.Cunn.) Kirk	14.8	91.214	41.046	0.041
Calophyllum obliquinervium Merr.	14.32	85.220	38.349	0.038
Canarium odontophyllum Miq.	16.71	117.307	52.788	0.053
Casuarina equisetifolia L.	33.42	493.580	222.111	0.222
Celtis paniculata (Endl.) Planch.	9.55	36.771	16.547	0.017
Celtis philippensis Blanco	10.03	40.685	18.308	0.018
Cordyline australis (G.Forst.) Endl.	19.1	154.718	69.623	0.070
Cratoxylum sumatranum (Jack) Blume	11.94	58.398	26.279	0.026
Dillenia luzoniensis Merr.	16.71	117.307	52.788	0.053
Drypetes grandifolia (C.B.Rob.)	147.06	10,647.193	4,791.237	4.791
Dysoxylum alliaceum (Blume) Blume.	176.18	15,485.141	6,968.313	6.968
Ficus ampelos Burm.f.	16.23	110.465	49.709	0.050
Ficus balete Merr.	14.32	85.220	38.349	0.038
Ficus variegata Blume	84.03	3,337.469	1,501.861	1.502
Gmelina arborea Roxb. ex Sm.	42.49	811.998	365.399	0.365
Hopea philippinensis Dyer	22.44	216.137	97.261	0.097
Hypobathrum racemosum (Roxb.)	102.65	5,053.758	2,274.191	2.274
Ilex cumingiana Rolfe	11.94	58.398	26.279	0.026
Lagerstroemia piriformis	489.4	128,736.017	57,931.208	57.931 i
Lagerstroemia speciosa (L.) Pers.	41.06	756.284	340.328	0.340
Lithocarpus solerianus (Vidal) Rehder	142.76	10,012.346	4,505.556	4.506
Macaranga grandifolia (Blanco) Merr.	15.76	103.836	46.726	0.047
Mangifera altissima Blanco	177.62	15,747.260	7,086.267	7.086
Mangifera indica L.	9.55	36.771	16.547	0.017*****
Melicope vieillardii (Baill.) Guillaumin	48.22	1,055.426	474.942	0.475
Morinda citrifolia L.	9.07	33.062	14.878	0.015****
Myristica philippensis Lam.	17.19	124.361	55.962	0.056
Palaquium dubardii Elmer	17.19	124.361	55.962	0.056
Palaquium luzoniense (Fern-Vill.) Vidal	26.74	310.787	139.854	0.140
Palaquium merrillii Dubard	232.52	27,524.347	12,385.956	12.386 vi
Pandanus exaltatus	4.77	8.739	3.933	0.004*
Parashorea malaanonan (Blanco) Merr.	196.72	19,460.385	8,757.173	8.757
Polyscias nodosa (Blume) Seem.	65.41	1,985.598	893.519	0.894
Prasoxylon alliaceum (Blume) M.Roem.	11.94	58.398	26.279	0.026
Pterocarpus indicus Willd	5.73	12.753	5.739	0.006**
Pterocarpus rotundifolius	72.57	2,462.812	1,108.265	1.108
Shorea astylosa	184.3	17,000.629	7,650.283	7.650
Shorea polysperma	13.85	79.437	35.746	0.036
Sterculia foetida L.	35.33	553.843	249.229	0.249
Sterculia rubiginosa Vent.	130.83	8,354.614	3,759.576	3.760
Swietenia macrophylla King	31.51	436.902	196.606	0.197
Syzygium garciae (Merr.) Merr.	218.68	24,235.034	10,905.765	10.906
Syzygium leucoxylon Korth.	102.18	5,005.152	2,252.318	2.252
Syzygium simile (Merr.) Merr.	12.41	63.345	28.505	0.029
Terminalia catappa L.	40.58	738.168	332.175	0.332
Tristaniopsis decorticata (Merr.)	9.07	33.062	14.878	0.015***
Vitex spp	14.32	85.220	38.349	0.038
Wrightia pubescens (Blanco) Ngan	369.56	71,916.659	32,362.497	32.362 iii
Xanthostemon philippinensis Merr.	435.45	101,050.576	45,472.759	45.473 ii
Xylopia brasiliensis Spreng.	11.94	58.398	26.279	0.026
TOTAL				250.949

i, ii, iii, iv, v, vi = Species with higher carbon stocks (tC/ha).
,,***,**** & ***** = Top 5 species with the lowest carbon stock (tC/ha). Note that one * indicates the first species with the lowest carbon stock, two * indicates the second species with the lowest carbon stock, three * indicates the 3rd species with the lowest carbon stock and so on.*

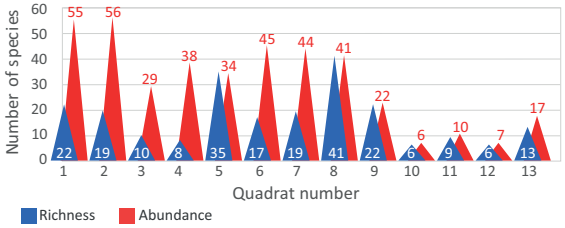


Figure 3 – Spatial variation in species richness and individual abundance across sample quadrats in the study area.

minimal biomass accumulation in these areas due to natural disasters, anthropogenic activities like illegal cutting of trees and traditional charcoal production. The discrepancies in carbon stock among the 13 quadrats are due to variances in vegetation structure, stand maturity, and species mix.

Species richness and abundance

Figure 3 showed noticeable spatial variation in species richness and abundance across quadrats. The highest species richness was recorded in Quadrats 8, 5, 1 and 9 (41, 34, 22 and 22 respectively), while the highest abundance index was observed in Quadrats 1 and 2 (55 and 56). Conversely, Quadrats 10-12 showed both low richness (6–9 species) and low abundance (6–10 individuals), reflecting disturbed vegetation structure.

The discrepancies among quadrats were due to the variances in vegetation and the presence of bigger trees that store more biomass. Quadrats exhibiting higher richness and abundance had moderate to high carbon stock values, indicating that structurally complex, species-diverse stands contribute more substantially to carbon storage. However, quadrats with low richness and abundance also showed low carbon stocks, signifying ecological degradation or environmental constraints on vegetation growth. This complex forest structure is largely driven by nutrient cycling within the soil, which contributes to the maintenance of a distinct microclimate that enhances biodiversity (Franklin & Spies 1991).

Conservation and endemism status

The 2023 IUCN Red List of Threatened Species revealed the endemism status of inventoried species. Figure 4 shows that most of the trees validated fell under the Unknown species (172) and Least Concern (126) categories. However, a substantial number of species were classified as Vulnerable (56) and Endangered (53). Fewer species were listed as Near Threatened (16), Data Deficient (17), Threatened (3) or Critically Endangered (1), indicating the importance of conservation of taxa within the study area.

Among the recorded species, *Shorea astylosa* and *Hopea philippinensis* Dyer are the most critically endangered, with severe population declines driven by historical overexploitation, extensive lowland forest loss, and limited natural regeneration, placing them at imminent risk of extinction. Their continued presence suggests that the forest functions as a critical refuge and that any further degradation could result in local or total extinction of these species. Therefore, Dibudalan warrants a high conservation priority to protect its remaining biodiversity because it is not just a matter of storing carbon but also of keeping the whole web of life going.

The species composition of the DMFR was strongly dominated by endemic taxa, accounting for 312 species (Figure 5). Native non-endemic species numbered 84, while introduced species were relatively few (43). Only five species had unknown endemism status, highlighting the predominance of locally restricted flora at the site.

The abundance of endemic species indicates that the DMFR supports a highly unique biological community shaped by long-term ecological and evolutionary processes after the total logging operations (DENR 1998). The small percentage of introduced species suggests that the ecosystem has managed to withstand biological invasions. The fact that only a few species, such as *Vitex* spp., have unknown endemism status shows that Dibudalan has a high level of taxonomic work. Generally, the overwhelming dominance of endemic species emphasizes the DMFR's critical role as an endemism hub of irreplaceable biodiversity. These observations suggest that any further disturbance or habitat loss could result in disproportionate biodiversity impacts, including the potential loss of species, thereby emphasizing the importance of prioritizing the conservation and sustainable management of the area.

Discussion

The findings indicate that the Dibudalan Mountain Forest Reserve encompasses a diverse array of tree species. Table 1 demonstrates the importance of the DMFR as a safe habitat for many tree species. These various kinds of trees formed the ecological structure and composition of the forest, mostly with lower diversity indices.

The accumulated diversity index (H') value recorded illustrates that the DMFR is a highly diversified stand. The five species with the highest relative abundances and the most significant contributions to the Shannon–Wiener diversity index were *Artocarpus odoratissimus*, *Lagerstroemia piriformis*, *Syzygium leucoxylon*, *Artocarpus blancoi* and *Xanthostemon philippinensis*. Among these, *Artocarpus odoratissimus* contributed the most to diversity (H' = 0.249), reflecting its structural dominance in the region. The dominance of these plant species is strongly influenced by their adaptability when it comes to thriving despite the edaphic stress associated with the ultramafic soils. According to Lazarus et al. (2011), ultramafic ecosystems demonstrate that soil chemistry controls plant distribution and dominance which restricts the set of metal-tolerant taxa that often account for the highest importance values in ultramafic forests. Furthermore, the ability of these stress-tolerant tree

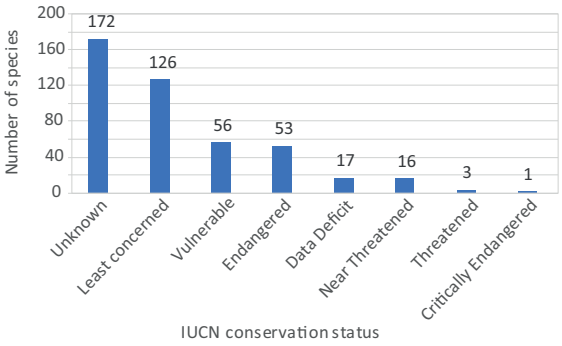


Figure 4 – Frequency distribution of recorded species according to IUCN conservation status.

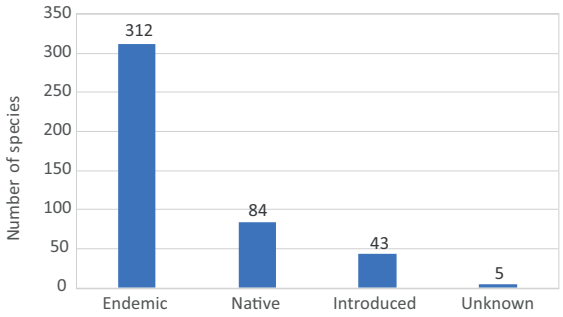


Figure 5 – Distribution of recorded species.

species to withstand environmental stresses enables them to persist and outcompete less-adapted species, making them the key components of the forest community, particularly at elevations of at least 239 m asl or 784 ft (Figure 1). These findings were supported by the studies of Fernando et al. (2008), Lasco et al. (2001) and Whitmore (1998), which affirm that stress-tolerant taxa are distributed across the elevations of 0 – 1,219.2 m asl in lowland and lower montane secondary forests. Similar patterns of study have been observed in the ultramafic forests of the Philippines and across Southeast Asia, showing that only a minority of species thrive under such harsh soil conditions (Proctor 2003; Brady et al. 2005).

The presence of a few mature species with larger diameters is clear evidence of the DMFR's disturbance from previous natural catastrophes (extreme typhoons and lightning) and anthropogenic activities, such as illegal timber poaching and kaingin making, leading to intentional forest fires. These natural disturbances and anthropogenic activities have affected the succession process, resulting in the Dibudalan Mountain Forest being characterized as a secondary growth forest. Another factor that exacerbated the mountain's deterioration is the construction of ASCOT buildings and other infrastructures, as well as the illegal cutting of premium species by neighbouring residents for economic purposes. Such events aided stress-tolerant species in growing and competing with others while limiting the growth of late-successional and disturbance-sensitive taxa. As a result, many small-diameter trees (less than 5 cm DBH) of stress-tolerant species swiftly regenerated, thereby increasing the overall number of species while preserving forest structure for carbon sequestration.

Compared to other mountains in the Philippines and Southeast Asia, the DMFR has higher species diversity. Similar values have been documented in the tropical mountain forests of Borneo and Sumatra, where their corresponding H' typically ranges from 3.0 to 4.0, as well as in the montane and protected forest landscapes of Mt Apo (Lasco et al. 2001; Slik et al. 2015).

The dominance of low-abundant species in terms of species richness leads to low evenness, while the weakness of high-abundant mature species in terms of richness makes high evenness (Table 2). The observed increase in evenness with abundance suggests that the most common tree species in the DMFR are more evenly distributed. This helps the Dibudalan Forest stand stay stable. Odum (1971) explains in *The Fundamentals of Ecology* that ecosystems with a more even distribution of biomass and abundance among species tend to show greater stability and resistance to fluctuations, whereas systems dominated by only a few species are more vulnerable. Tilman (1996) further argues that greater species diversity and evenness can stabilize ecosystem processes by reducing fluctuations through compensatory dynamics among species. However, the poor evenness that accompanies the high richness of low-abundance species indicates that many uncommon or sparsely distributed species are present a typical feature of secondary and selectively disturbed mountain forests (Brown & Lugo 1990).

Table 3 presents a total carbon sequestered of 250.949 tC / h, demonstrating that a few mature trees of large-diameter species, such as *Lagerstroemia piriformis, Xanthostemon philippinensis* and *Wrightia pubescens*, are mainly contributors to carbon storage in the DMFR. This pattern was observed in both tropical and temperate forests, reflecting a common structural trend in which a few emergent and canopy species dominated the total carbon stocks despite high overall species diversity (Bhatia 2014; Brown 1997; Chave et al. 2014; Keith et al. 2009). The positive relationship between DBH and Carbon Stock emphasizes the ecological importance of conserving large-diameter trees, which store disproportionately high amounts of carbon and exhibit long residence times. In other words, a positive DBH–carbon stock relationship indicates that larger trees store more carbon and retain it for longer periods, making them vital for long-term carbon sequestration and forest stability. Along with the findings from Southeast Asian forests (Keith et al. 2009), European temperate forests (Fennessy & Beers 2023) and southeastern Australian mixed forests (Fedrigo et al. 2014), this research output reinforces the global relevance of protecting structurally dominant trees for climate regulation.

Smaller understory species, such as Pandanus exaltatus and Pterocarpus indicus, contribute less to total

carbon but play a crucial role in maintaining biodiversity and ecosystem resilience. This functional balance between carbon-dominant and diversity-supporting species is essential for preserving forest structure, habitat complexity, and ecological processes. The existence of large trees (Table 3) indicates the presence of old-growth forest remnants, which are becoming increasingly rare yet serve as long-lasting carbon repositories and help maintain ecological stability over time. These old, large trees are increasingly becoming rare due to damage from typhoons, which eventually leads to their death, and due to the illegal timber cutting by others selecting these mature trees for survival purposes. The DMFR's carbon stock of 250.95 tC / ha is within the upper range of values reported for tropical forests in the Philippines (Lasco et al. 2001; Corpuz et al. 2015).

In essence, this study demonstrates that the DMFR's carbon storage is dominated by a few large, high-biomass species, underscoring their ecological and climate-regulatory importance. Effective forest management should therefore prioritize the conservation of these carbon-dense species while maintaining overall species diversity to ensure a long-term ecosystem resilience and sustained carbon sequestration.

Conclusions

A Shannon-Weiner diversity index (H') of 3.543 shows that the DMFR is a highly diversified stand supporting highly significant tree species. A few mature species such as *Lagerstroemia piriformis, Xanthostemon philippinensis, Wrightia pubescens* and *Artocarpus odoratissimus* contribute the most to the 250.95 tC / ha total carbon sequestered. Large-diameter trees serve as key carbon reservoirs, while smaller understory species maintain biodiversity and structural complexity. Carbon stocks vary across quadrats, reflecting differences in stand maturity and disturbance, with degraded areas showing reduced biomass. DMFR management should prioritize the protection of carbon-dense species, foster the recruitment of medium-sized trees and restore disturbed areas to integrate climate mitigation with biodiversity conservation, thereby ensuring the DMFR's long-term resilience and ecological integrity.

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The Zillertal Alps High Mountain Nature Park anchored in the region by dedication of all involved

Valerie Braun, Willi Seifert, Gudrun Steger, Paul Steger, Annemarie Polderman & Katharina Weiskopf

Keywords: Nature Parks, stakeholder participation, park management

Abstract

The Zillertal Alps High Mountain Nature Park, situated at the southern end of the Zillertal valley and bordering Italy, serves as an example of long-term protected area management in the Austrian Alps. It was designated a protected area in 1991 and officially declared a nature park in 2001. Alongside the Hohe Tauern National Park, it was the first protected area in Tyrol to introduce its own administrative structure for managing a protected area. This article examines the park's development, its governance model and its current management practices. It highlights the role of local participation, inter-institutional cooperation and strategic communication in fostering acceptance and ensuring long-term success. Key initiatives such as the founding of the Nature Park Association and the establishment of a Nature Park Council; the creation of the Nature Park Centre; and the integration and participation of the local population through the establishment of Nature Park partner schools in the education sector and in partner businesses (accommodation) from the tourism sector have all strengthened the nature reserve's integration into the region at various levels. In recent years, the focus has been on nature conservation and research, thereby significantly intensifying on-the-ground activities and strengthening efforts to document regional biodiversity scientifically, as well as to make contact with landowners and land managers. The paper also addresses current challenges, including climate-related natural hazards and land-use conflicts in Alpine agriculture.

Profile

Protected area

Zillertal Alps High Mountain Nature Park

Mountain Range

Alps

Country

Austria



Figure 1 – Zillertal Main Ridge. © Andi Neurauter

Introduction

Since the establishment of the first nature parks in Austria in the 1960s as recreational areas for the people of Vienna, nature parks have evolved into areas in which their four objectives – conservation, recreation, education and regional development – are given equal priority. In Tyrol, an additional objective of research is also included. Nature parks that succeed in developing all these functions simultaneously have the opportunity of establishing themselves as model regions for sustainable development. Sustainable objectives are implemented in nature parks through regional governance involving stakeholders from politics, administration, business and civil society. In this context, regional governance acts as the operational interface through which sustainable development is implemented, enabling the coordination of diverse stakeholder interests and the co-production and realization of the nature parks' objectives.

This paper examines the development and governance of the Zillertal Alps High Mountain Nature Park (Austria) as a long-term case of protected area management in the Alps. Established in 1991 and designated as a nature park in 2001, the park represents one of the first protected areas in Tyrol with its own dedicated administrative structure. Over more than three decades, it has evolved into a multifunctional system that combines nature conservation, sustainable tourism, environmental education and scientific research.

Drawing on document analysis and insights from practitioners and stakeholders, the paper analyses (1) the evolution of the park's governance structures, (2) mechanisms fostering stakeholder participation

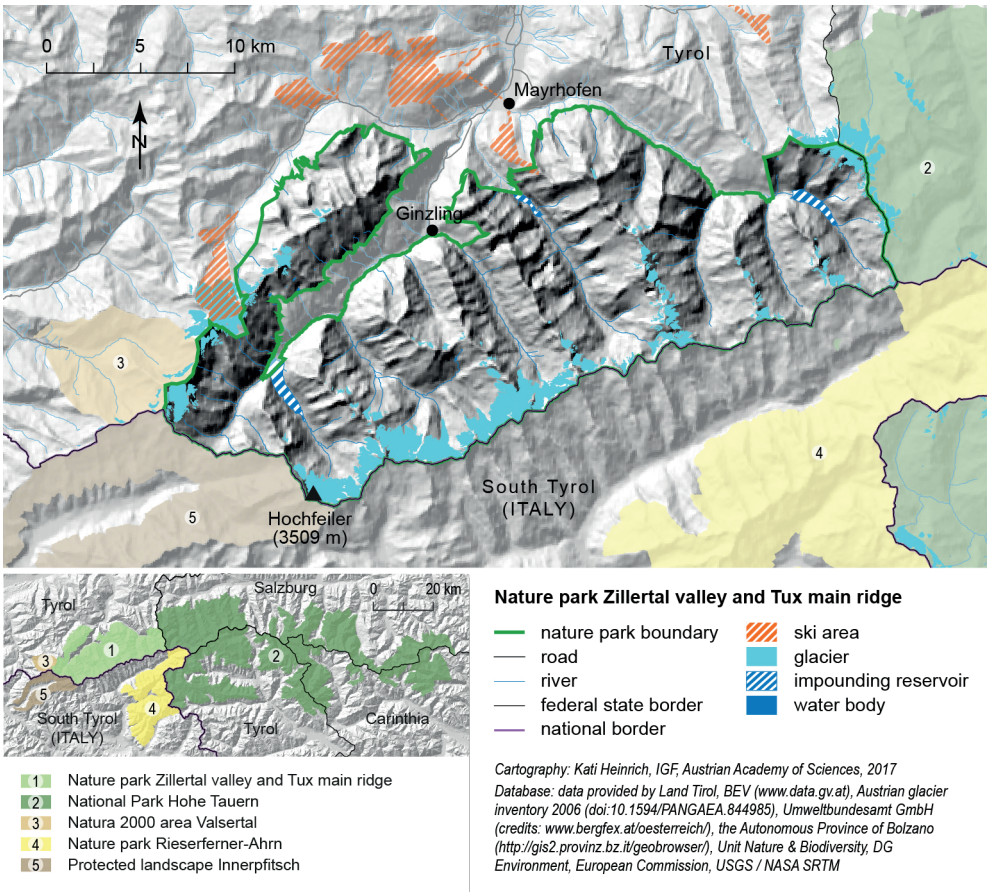


Figure 2 – Map of the Zillertal Alps High Mountain Nature Park study area and its adjacent protected areas (Braun et al. 2018).

and regional acceptance, and (3) current challenges related to land use, climate change and long-term funding. By doing so, it aims to identify key factors that enable the integration of conservation and regional development in a high-mountain protected area.

Study area

The Zillertal Alps High Mountain Nature Park (ZNaP) is situated in the southern part of the Zillertal valley (Figure 1 & 2), in the Austrian province of Tyrol on the border with Italy, and spans five municipalities (see Info Box). Three of these five municipalities are heavily oriented towards tourism, with large ski resorts and accommodation facilities, whilst the other two have not participated in this development. In 2025, the population of the ZNaP municipalities was 7,697 with 2,149,080 overnight stays in winter and 1,541,375 in summer (Amt der Tiroler Landesregierung 2026). Ginzling, one of the two less tourism-driven villages, became the administrative centre of the ZNaP in 2008 following the decision to locate the ZNaP visitor centre there. The ZNaP's altitude ranges from 1,000 m asl in the village of Ginzling to 3,509 m asl at the summit of the Hochfeiler. The landscape is shaped by its geological history, which has left behind a mountain range with steep peaks, steep gradients, numerous side valleys in a confined space, a marked abundance of crystals and a juxtaposition of silicate rock and the Hochstegen limestone formation. The landscape was given its final shape by the alternation of several glacial and interglacial periods and the advance and retreat of the ice masses that carved out the valleys (see Figure 2).

The result is a diverse mosaic of habitats, ranging from predominantly agricultural valleys to often steep mountain forests, alpine pastures and alpine grasslands leading up to glaciers and new terrain at the glacier forefields resulting from glacier melt. Among the particularly valuable or protected habitats are floodplains, hillside and ravine forests, mountain hay meadows, moors and wetlands.

The protected area was established as early as 1991 and was additionally designated a Nature Park by the Tyrolean provincial government in 2001. In 2016, large sections of the Tux Main Ridge (Figure 3) were incorporated into the existing ZNaP, which now covers an area of 422 km²; previously, it covered 372 km². Together with the adjacent Rieserferner-Ahrn Nature Park and the Innerpfitsch Landscape Conservation Area on the Italian side, as well as the Valsertal Nature Reserve and the Hohe Tauern National Park (Carinthia, Salzburg, Tyrol) on the Austrian side, it forms part of Central Europe's largest network of protected areas, covering more than 2,700 km², see Figure 2 (Weiskopf & Seifert 2015; Braun et al. 2018).



Figure 3 – View towards the Tux Main Ridge which was incorporated into the existing protected area in 2016. © Paul Sürth

How it all began

Following the designation by the Province of Tyrol of a regionally recognized protected area known as the *Ruhegebiet* (quiet area), a manager was appointed as early as 1992 to draw up a landscape framework plan with measures for the quiet area. In 1996, a key step was the founding of the Nature Park Association and its Council (Fischer 1992, 1997), see below *Establishment of a Nature Park Council*.

In the early years of the quiet zone, the focus of the management was on working with the local population to strengthen nature conservation efforts and to foster an emotional connection with the area (Konstenzer 1997). To raise awareness among local stakeholders, a symposium organized jointly by the management and the Austrian and German Alpine Associations in 1997 outlined the management's main tasks: landscape conservation, increasing public acceptance, improving the quality of protection and promoting regional networking (Hasslacher 1997).

One of the initial priority actions was to offer temporary exhibitions in Ginzling. From 1997 onwards, annual exhibitions were held on various themes, such as smugglers and poachers, stories about stones, herbs and alpinism. These exhibitions continued until 2008, when the permanent *Gletscher.Welten* (glacier.worlds) exhibition was set up in the newly built Nature Park Centre. The initial exhibitions were organized and supported by the ZNaP management in collaboration with local residents in the elementary school of Ginzling. This also fostered regional cooperation with stakeholder groups in the early years of the ZNaP.

The Tyrolean Nature Conservation Act of 1997 first enshrined the management of protected areas within contractual nature conservation, but it was not until 2005 that the Tyrolean provincial government adopted a protected area management concept. The regional development strategies provide for *the implementation of the protected area management concept, including the establishment of the protected area platform and a coordination office* (Land Tirol 2007). Protected areas *constitute an essential element of nature conservation work in Tyrol. Therefore, activities in protected areas should be stepped up, particularly in the areas of management, monitoring, public relations, regional development and communication with landowners* (Land Tirol 2007). In 2006, the Tyrolean Protected Areas Coordination Office was established within the Provincial Department of Environmental Protection to implement and strategically align the protected areas.

By 2010, the protected areas in Tyrol were to be more closely integrated within tourism objectives so as to enhance the value of nature whilst ensuring that nature conservation remained the primary objective (Land Tirol 2010). This objective was achieved through efficient protected area management, which created the framework for effective visitor management to *prevent visitors from damaging natural assets worthy of protection* (Land Tirol 2010). By appointing a manager as early as 1992, the ZNaP was ahead of its time.

Infobox

Zillertal Alps High Mountain Nature Park
Nature Park municipalities: Mayrhofen, Tux, Finkenberg, Brandberg and Ginzling (a small village which is part of Mayrhofen).

1991: Established by the Tyrolean provincial government as a Quiet Area covering 372 km².
1992: A manager was appointed for the Quiet Area.
1996: Founding of the Nature Park Association.
1997: Main tasks outlined for the nature park's management.
1997: First exhibitions in Ginzling at the elementary school.
2001: Designated a Nature Park.
2008: Opening of the Nature Park Centre in Ginzling.
2008: Ginzling joined the *Bergsteigerdorf* (Mountaineering Village) network.
2009: The first Nature Park school partnership starts in Brandberg.
2016: Extension of the Quiet Area and the Nature Park. Size since then, 422 km².
2018: A new staff position dedicated to nature conservation and research created as part of the Nature Park's management.
2023: Opening of the Nature Park Centre extension in Ginzling.

From Quiet Area to Nature Park

The term *Quiet Area* initially led to misunderstandings among both locals and tourists. People asked whether they were not allowed to speak there, i. e. whether *peace and quiet* had to prevail there. The regional benefits of a quiet zone were not immediately apparent. It was only with the *Nature Park* label and the new Zillertal Alps High Mountain Nature Park name that a new awareness was created.

Under the Tyrolean Nature Conservation Act, nature parks are publicly accessible (large-scale) protected areas – such as landscape conservation areas, quiet zones or nature reserves – particularly suitable for recreation in the great outdoors or for environmental education, and whose conservation is of particular importance.

Management of the protected area

The protected area has been continuously managed since 1992. In accordance with the ZNaP's mission statement, the administration is responsible for all organizational tasks relating to the ZNaP. The administration consists of a full-time managing director and one other full-time employee. The specific remit of all administrative staff is governed by the statutes of the Nature Park Council, the mission statement in force at the time, employment contracts and by-laws / regulations.

Establishment of a Nature Park Council

In 1996, the municipalities within whose boundaries the ZNaP is located, the Province of Tyrol and the Austrian Alpine Association founded a Nature Park Association who is represented and led by a Council. All its members are rooted in the region (Seifert 2007). The Nature Park Council, which supports the ZNaP was a novelty in Tyrol, as until then staff of the Tyrolean provincial government had been responsible for the protected areas (ibid.).

The number of full members has grown steadily since the Nature Park Association was founded. This is attributable to the ZNaP's greater integration within the tourism sector through tourism associations in 2004 and again in 2008. In addition, cooperation with Österreichische Bundesforste AG (Austrian Federal Forests), the largest landowner in the ZNaP, was intensified from 2011 onwards. Following the expansion of the ZNaP in 2008 and again in 2016 towards the municipal area of Tux, which had not previously been represented in the Nature Park Association due to its lack of a share in the protected area, Tux was now also included. Today, the Nature Park Council is the decision-making body for all important or strategic matters concerning the operational work and development of the ZNaP.



Figure 4 – Volunteer project on an overgrown pasture in the Nature Park region. © Zillertal Nature Park

Funding of the administration

Funding for the ZNaP administration was initially provided by the Austrian Alpine Association (1991). Following the creation of the Landscape Framework Plan (1992), the Austrian Alpine Association and the Province of Tyrol jointly funded the appointment of the first protected area manager. After the establishment of the Nature Park Association, the Association's members increased the budget to fund the administration staff (Fischer 1997). Currently, the Province of Tyrol, co-financed by European Union grants, covers approximately half of the personnel costs for the ZNaP's management; the other half is provided by the five ZNaP municipalities, the Austrian Alpine Association and the two tourism associations of the ZNaP region.

In addition, the Nature Park's partner businesses make a significant contribution to the Association's funding through their financial contributions as part of the tourism services group. About 100 businesses have signed agreements to work closely with the ZNaP. To become a Nature Park partner business, a company must meet various quality criteria, commit to the ZNaP's philosophy, and help to convey the ZNaP's concepts directly to its guests (High Alps Nature Park Zillertaler Alps 2026).

The German Alpine Association (DAV), with its sections active in the ZNaP region, Nature Park supporting members contributing an average amount of EUR 25 and private sponsors also make a valuable contribution to core funding. The ZNaP also receives funding from various national and international project schemes such as LEADER and INTERREG, which is used to cover project-related staff and material costs.

Acceptance

Three acceptance studies have already been conducted (Sandner et al. 1996; Fröhlich & Ott 2008; Mayrhauser 2015), which show that the public's at-

titude towards the ZNaP has become more positive overall and that general awareness of the ZNaP has risen from 78% (1996) to 86% (2015). This was also evident during the expansion of the ZNaP in 2016. During the relevant discussions conducted by political representatives, the chairperson of the Nature Park Association and the managing director of the Nature Park with the landowners, a good general mood and a broad consensus emerged, which had a positive impact on the decision-making process.

The ZNaP team and council have observed that acceptance among landowners and farmers has increased significantly, partly due to several nature conservation and volunteer projects (Figure 4) organized by the ZNaP on alpine pastures and in the mountain forest within the ZNaP. The 2015 acceptance study by Mayrhauser also showed that scepticism on the part of representatives of the agricultural sector has decreased significantly since 1996. However, the defensive stance, particularly among farmers, which is evident in all three studies, as well as their fears of a *restriction of their property rights*, are diminishing but continue to remain a challenge for the administration.

The Nature Park Centre

A milestone for the ZNaP was the opening of the Nature Park House in Ginzling in 2008. The building housed the ZNaP office, the Ginzling local council, the tourist information centre, an exhibition on glaciers, a library and a small shop. Following renovation and extension from 2022 to 2023, the building was significantly enlarged and now houses a new exhibition on the geological history and crystal treasures of the Zillertal Alps, which have been loaned free of charge by numerous private collectors. The integrated café that was also created has proved to be a valuable addition to the visitor experience and has great potential to develop into a social meeting place, also for the inhabitants of Ginzling. A nature garden and a play area with a bouldering block complete the visitor facilities. Half of the funding for the extension came from the region (the ZNaP's municipalities and tourism associations), whilst the other half was financed through various funding schemes, in particular through a substantial financial contribution from the Province of Tyrol.

Bergsteigerdörfer – Mountaineering Villages

The *Tourism and Leisure* Protocol of the Alpine Convention signed in 1998 (Alpenkonvention 1998) aims to strengthen the competitiveness of nature-based tourism and to strike a balance between intensive and extensive forms of tourism. As early as 2001, the first concept paper on *The Network of "Mountaineering Villages" in the Alps* was drawn up on behalf of the Austrian Alpine Association to promote a form of mountain tourism adapted to the region and based on



Figure 5 – Rock ptarmigan (Lagopus muta). © Evelyn Seppi

sustainability criteria (Kals 2006). The Austrian Alpine Association and the ZNaP association worked on a concept for Ginzling to improve the Alpine tourism offering and integrate it into this network. Since 2008 Ginzling has been part of the network.

The *Bergsteigerdörfer* initiative, which aims to make nature-oriented and resource-conserving tourism competitive, goes hand in hand with the ZNaP's objectives for promoting regional development. In this way, the *Bergsteigerdörfer* initiative complements and supports the ZNaP's objectives and presents them as a cross-border, cross-regional and cross-cultural network of 43 locations in 5 Alpine countries (Bergsteigerdörfer 2026). In 2016, the initiative was recognized as an official implementation project of the Alpine Convention.

Nature conservation objectives as a catalyst

The development of the nature conservation objectives began in 2018 and was concluded in 2020 with a resolution by the Nature Park Council. During the process, the ZNaP management defined and described the characteristic habitats, along with the measures required to conserve, improve or restore them (Hochgebirgs-Naturpark Zillertaler Alpen 2020). The habitats include mountain forests, wetlands, alpine pastures, alpine grasslands, as well as rocky and high-mountain sites. The formulation of these objectives provided an important impetus for concrete action, such as nature conservation projects in the Glocke Protected Landscape Area, in the riparian forest on the Schwemmalm (an alpine pasture) and in the mountain forest, or various so-called *nature conservation plans in the alpine pastures*.

Mission statement of the Nature Park

The ZNaP Strategy, which serves as a mission statement setting out the direction for the ZNaP's strategic and operational work, was developed jointly by the Nature Park Council and the full-time staff of the ZNaP Management Team. The first edition of the mission statement was adopted in 2014 and remained

in force until 2020. In 2024, work began on revising and reissuing the document, and the process was completed in 2025. The updated mission statement is in force from 2025 to 2032. Key stakeholders such as the Nature Park partner schools, regional producers and the Nature Park's partner businesses were involved in the process. This resulted in the following objectives:

- Sharpen the profile of the ZNaP and document changes in the ZNaP area.
- Conduct more thorough research into the fauna and flora of the ZNaP area and expand species lists.
- Exploit synergies and strengthen cooperation with universities and other institutions.
- Clearly define research objectives and communicate results effectively.
- Collaborate on research beyond the ZNaP's boundaries to preserve the wider ecosystem.
- Establish a better foundation and gain more knowledge about *new territory* released by the glacier.

Nature Park partner schools

In collaboration with the ZNaP, Nature Park partner schools place particular emphasis on teaching nature-related topics. Topics relevant to the ZNaP are taught in separate Nature Park partner school lessons and put into practice in joint projects. Many of the projects taking place at the ZNaP are incorporated within the Nature Park partner schools. The Nature Park partner schools have played a key role in increasing public acceptance of the ZNaP by enhancing its profile and standing among local families. The first collaboration took place in 2009 with the Brandberg elementary school. The school environment offers a valuable opportunity to strengthen environmental education and awareness, as schools where science is taught in a more practical manner produce pupils with a higher level of environmental awareness (Coertjens et al. 2010).

The Nature Park and research

The development of nature conservation objectives and the creation of a new staff position dedicated to nature conservation and research (2018) have given these two areas significantly greater weight within the ZNaP's remit. Due to the high financial and personnel costs involved, as well as the specialist expertise required, the vast majority of research questions are addressed and processed in collaboration with universities and other research institutions. For example, recent projects have included surveys on the spatial behaviour of the Alpine ibex (2016–2020), natural landscape analyses and management concepts for specific valley and mountain forests, as well as butterfly and vegetation mapping in the Brandberg mountain meadows area (2020–2025). In addition, a long-term monitoring programme for the rock ptarmigan was launched in 2019, and an update of the *Zillertal Alps Glacier Study* was implemented (see Heinen 2026).

Challenges

Agriculture in the Nature Park

In the Zillertal, the cultural landscape is intensively farmed up to an altitude of over 2,000 m asl, often for dairy farming. The alpine pastures have been used by people and livestock for many centuries, and in some cases even for millennia. In terms of area, they account for a significant proportion of the ZNaP and cover around a quarter of the protected area. Some alpine pastures begin as low as 1,200 m asl, as the valleys are very steep and narrow. Cattle are the primary livestock grazed on these pastures, though sheep, goats and horses are also kept (Hochgebirgs-Naturpark Zillertaler Alpen 2020). However, too much fertiliser is used on some alpine pastures, leading to structurally poor, nutrient-rich meadows and the loss of species-rich rough pastures. Another significant problem is rock extraction from alpine pastures. Under the pretext of *improving agricultural infrastructure*, alpine pastures are being cleared of rocks on a large scale using machinery. Diverse, mosaic-like alpine pastures, with distinctive cultural landscape features such as gneiss and granite boulders, are thus being transformed into monotonous alpine grasslands. Another reason for this is the high quality of the rock material, which is in high demand for use in river engineering, road construction, slope stabilization and residential building. Discussions are currently underway between the ZNaP and authorities, politicians and other key stakeholders to reverse this trend and prevent the haphazard clearing of the landscape.

Climate change

Although not directly relevant to the work of the ZNaP, climate change and its associated impacts nevertheless pose a major challenge to the natural environment and various human activities in the region. On the one hand, there are rising temperatures, longer heatwaves and dry spells, greater variability in rainfall combined with increased heavy rainfall, decreasing snowfall, glacier retreat and the thawing of permafrost. On the other hand, there are issues related to agricultural land use, groundwater and drinking water, the safety of alpine infrastructure and, above all, the impact of the changes outlined on flora and fauna. The ZNaP seeks to contribute relevant foundational knowledge through appropriate research and, at the same time, to raise awareness so as to support important transformation processes within society.

Long-term funding outlook

Current developments in the economy, politics and society pose major challenges for non-profit organizations, which are very often heavily reliant on public funds and grants. This is because the noticeable

strain on public budgets, from local authorities right up to the EU level, is leading to a shortage of available funds. This is creating major uncertainties with regard to solid, long-term funding for privately or semi-publicly organized protected area management bodies. This is particularly serious because the quality and success of a protected area management organization's work depend significantly on long-term, stable employment relationships. In the coming years, great attention will need to be paid to maintaining precisely this stability in terms of the solid core funding that has characterized the Nature Park Association to date.

Conclusion

The Zillertal Alps High Mountain Nature Park is a model for protected area management in Tyrol, as it combines nature conservation, education, sustainable tourism, research and regional development. From its beginnings as a Quiet Area to its current role as a nature park, the park has undergone a remarkable transformation, characterized by cooperation between authorities, local communities, the tourism sector, Alpine Associations, the scientific community and nature conservation stakeholders.

A key factor in the park's success is its locally rooted administrative structure, which fosters trust, facilitates cooperation and ensures that nature conservation objectives are aligned with the needs of local residents. The establishment of the Nature Park House, the development of the Nature Park partner schools, research activities and the active involvement of local communities and tourism stakeholders have contributed to the park's visibility and acceptance. The *Bergsteigerdörfer* initiative further strengthens the link between sustainable tourism and regional identity.

At the same time, the ZNaP faces complex challenges – ranging from increasing natural hazards linked to climate change, through tensions regarding agricultural practices and ecological integrity, to securing long-term, stable funding for the protected area staff, who provide the foundation and backbone of the Nature Park Association. These challenges require adaptive management, continuous dialogue with stakeholders and clear communication of nature conservation objectives.

Overall, the ZNaP demonstrates how protected areas can serve as catalysts for both ecological conservation and regional vitality. Its development offers valuable insights into how conservation and use can be reconciled, acceptance fostered and nature conservation implemented in a multifunctional Alpine landscape.

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Sustainable heritage: Protecting Jingmai Mountain's traditional homes for ecotourism and rural development

Chunping Xie & Erlin Tian

Keywords: heritage preservation, sustainable ecotourism, traditional architecture, rural development, human-nature coexistence

Abstract

Jingmai Mountain represents an exceptional socio-ecological system defined by a long-standing model of human-nature coexistence, where traditional stilt houses function as essential hubs for tea production and environmental regulation. This study employs a qualitative multi-method approach, including field observations and semi-structured interviews, to examine how these traditional structures navigate rapid rural transformation and the material transition from indigenous timber to concrete. By analysing diverse stakeholder perspectives including those of elderly residents, local craftspeople and young urban migrants, the research identifies the ways in which socio-economic disparities and generational priorities lead to unequal decision-making in heritage maintenance. The findings suggest that integrating community-led restoration with managed ecotourism provides a viable pathway for maintaining architectural authenticity while addressing contemporary livelihood needs in mountain protected areas. Ultimately, this study offers a theoretical framework for understanding how high-altitude ethnic settlements can maintain ecological and cultural integrity while navigating the pressures of modernization and demographic shifts.

Profile

Protected area

Cultural Landscape of Old Tea Forests of the Jingmai Mountain in Pu'er

Country

China

Introduction

Nestled in the mountainous terrain of Yunnan Province, Jingmai Mountain achieved global recognition in 2023 with its designation as a UNESCO World Heritage Site (Li et al. 2023b; Zhang et al. 2025). This distinction celebrates not only its ancient tea gardens, which have flourished for over a millennium, but also the remarkable architectural heritage embodied in the traditional stilt houses of the Bulang and Dai ethnic groups (Chen & Hu 2024). These bamboo and timber structures function as integral components of a socio-ecological system. Beyond providing residential space, they facilitate the practical integration of human habitation with natural processes, incorporating traditional technical knowledge and historical settlement patterns that define Jingmai's cultural landscape. However, it is important to recognize that these architectural forms hold different meanings for different community members. Elderly residents may view them primarily as ancestral heritage and cultural identity markers, while younger generations may weigh their cultural significance against practical considerations of maintenance, durability and compatibility with contemporary lifestyles (Vázquez-Atochero 2025). The Bulang and Dai communities, despite sharing the geographic landscape, maintain distinct architectural traditions and may have different perspectives on preservation priorities (Xu et al. 2005). Understanding these diverse viewpoints is essential for developing preservation approaches that serve the actual needs and aspirations of those who inhabit these structures.

The traditional homes of Jingmai, adorned with the Bulang's *one bud, two leaves* decorations and the Dai's elegant ox-horn motifs, stand as physical manifestations of the *tea ancestor* belief system that governs local life (Zheng 2016). These structures embody ecological wisdom through their sustainable use of local materials, designed to harmonize with the region's wet climate and integrate seamlessly with ancient tea gardens and protective forests. They evoke a profound sense of xiangchou (nostalgia for one's homeland), connecting generations to their roots and preserving the stories of ancestors who cultivated tea and culture in harmony with nature (Zou 2018; Li 2019). These structures represent long-term adaptive strategies for sustainable living. They provide empirical data on balancing socio-economic requirements with environmental management practices developed over extensive periods of habitation.

Yet, this architectural heritage faces unprecedented challenges in the 21st century. Modernization, coupled with significant rural-urban migration, threatens to erode the cultural foundations that have sustained Jingmai's unique landscape. The migration of younger generations to urban centres, motivated by economic opportunities and contemporary lifestyle aspirations, precipitates a critical *brain drain* within mountain socio-ecological systems (Xiao et al. 2021). This phenomenon extends beyond demographic shifts to represent a

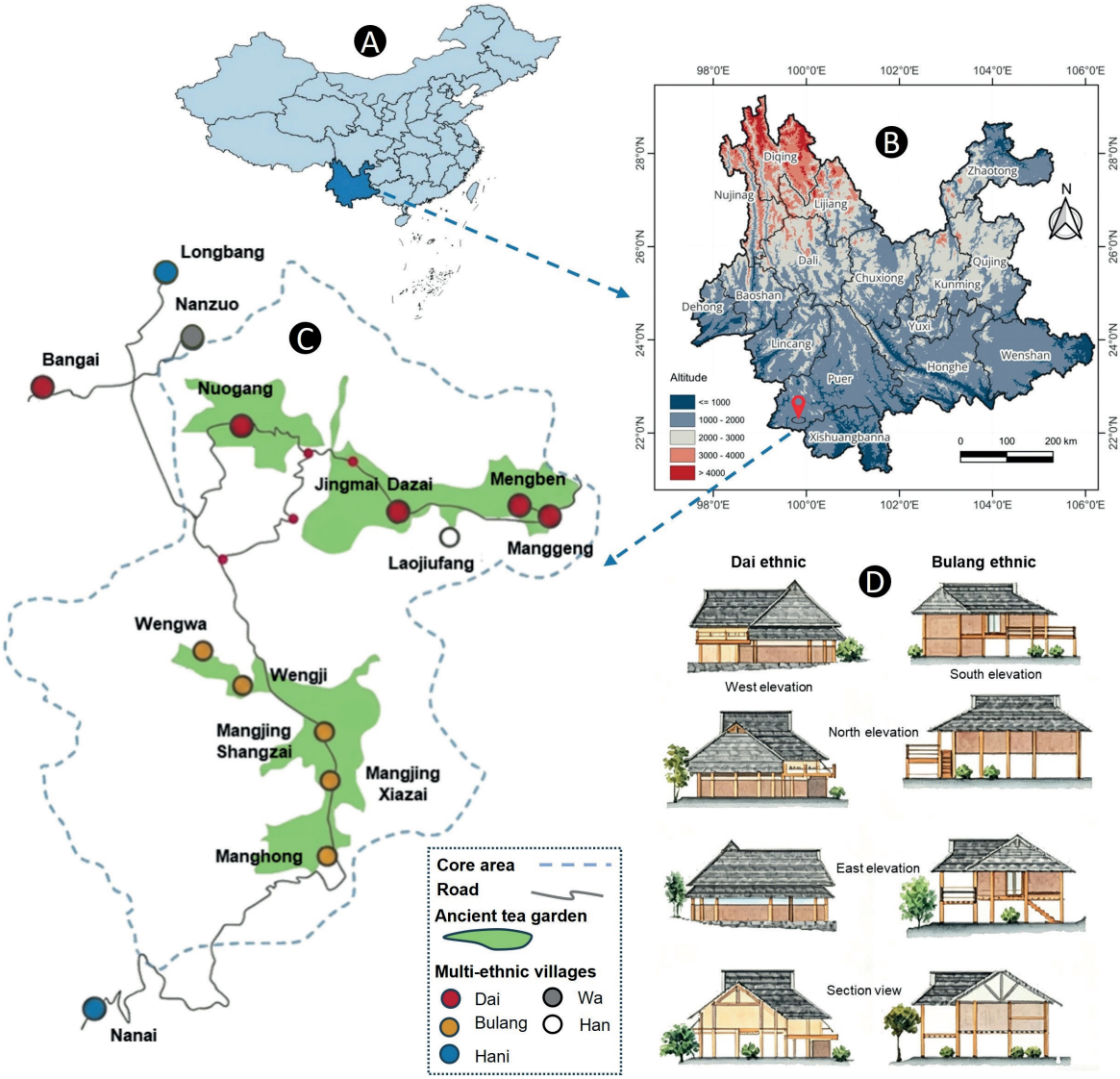


Figure – Jingmai Mountain World Cultural Heritage Core Zone, Yunnan, China. (A) Approximate location within China; (B) approximate location within Yunnan Province; (C) distribution of ethnic villages; and (D) traditional stilt dwellings of the Dai and Bulang people. The traditional Dai stilt house in Jingmai has a floor area of 100–180 m², with a raised ground floor that is light and transparent; the first floor consists of a front porch, a main room, a sun terrace, etc. The traditional Bulang stilt bamboo house in Jingmai has a floor area of 60–160 m², generally consisting of a raised ground floor and stairs, with a flexible layout that adapts to irregular terrain (Subfigure D was redrawn from Chen Dugui, People's Daily (Overseas Edition), Oct. 16, 2023).

fundamental rupture in the intergenerational transmission of indigenous knowledge (Li et al. 2023a; Zhao et al. 2025). Specifically, as the primary practitioners of traditional construction move away, the specialized tacit knowledge required for the maintenance and repair of bamboo and timber structures faces a high risk of extinction. This systemic loss of expertise undermines the community's capacity for autonomous heritage management, rendering traditional architectural forms increasingly vulnerable to physical decay and structural replacement. This cultural erosion not only jeopardizes Jingmai's heritage, but also diminishes the inspiration these homes provide for sustainable living worldwide.

In addressing these challenges, we adopt a research perspective that moves beyond viewing architecture merely as physical artifacts requiring protection. Instead, we examine traditional building practices as ongoing social processes involving knowledge transmission, economic decision-making and identity negotiation among diverse community members (Shrestha et al. 2025). This approach recognizes that preservation outcomes depend not only on policy interventions, but also fundamentally on how different stakeholders (Fortnam et al. 2023) – craftspeople, residents, young migrants, tourism operators and local officials – navigate the tensions between heritage conservation and contemporary livelihood needs. By engaging with this complexity, we aim to contribute insights relevant to heritage conservation challenges faced globally in the 21st century.

This study examines the functional role of traditional stilt houses within Jingmai Mountain's cultural



Figure 2 – Typical bamboo and timber structures in Jingmai Mountain. Traditional stilt houses of the Dai and Bulang ethnic groups, respectively (A and E). The primary building materials are wood and bamboo, with commonly used timber species including Schima spp., Quercus spp. and Pinus spp. The roofs of Dai houses typically feature double eaves and are adorned with decorative yellow ox horns at both ends of the ridge (C), while Bulang houses usually have single-eave roofs with ridge-end ornaments in the form of 'one bud and two leaves' (D). The lower level of the houses serves as the stilt space (B), traditionally used for storage or keeping livestock, though its function has often changed in modern times. F is the village centre, where various traditional rituals and ceremonies are held. © all pictures Chunping Xie

landscape and analyses the socio-economic factors shaping their current transformation. Rather than focusing solely on preservation as a static goal, this research investigates how various stakeholders – including local ethnic communities, heritage authorities and tourism developers – negotiate architectural change amidst rapid rural transformation. Understanding these negotiation processes is critical for mountain protected areas, where the maintenance of traditional dwellings is inextricably linked to the stability of the broader socio-ecological system. By evaluating the impact of cultural erosion, rural-urban migration and material substitution, this article identifies pathways for integrating community-led management with sustainable ecotourism. This approach aligns architectural heritage with rural sustainability, offering a model for how mountain socio-ecological systems can navigate the pressures of modernization while maintaining the ecological and cultural integrity of their landscapes.

Methods

Jingmai Mountain is located in Lancang County, Pu'er City, Yunnan Province, in southwestern China, at an altitude between 1,100 and 1,570 m. It has a mild, humid subtropical climate with an annual mean temperature of about 18 °C and annual precipitation of 1,400–1,450 mm. The mountain is covered by well-preserved evergreen broadleaf forests, with a forest coverage rate of 83.14%, and hosts a rich diversity of flora and fauna. Jingmai Mountain is home to five ethnic groups – the Dai, Bulang, Hani, Wa and Han – who have coexisted for centuries (Figure 1). The mountain is also renowned for its traditional *under-story tea cultivation* system, where tea trees grow under the shade of natural forests. Its 28,000 mu (approx. 1,866 hectares) of ancient tea forests have been recognized as the best-preserved, largest and most time-honoured old tea plantations in the world.

This study employs a qualitative multi-method approach to analyse the architectural transformation of Jingmai Mountain within its mountain socio-ecological system. Primary data were gathered through exten-

sive field observations and site surveys in traditional Bulang and Dai villages to document the structural characteristics of dwellings and the physical transition from timber and bamboo to concrete materials. To identify and examine diverse stakeholder perspectives, semi-structured interviews were conducted with a stratified group of participants, including resident households, village elders and local craftspeople. These actors were categorized by ethnic identity (Bulang and Dai), generational cohorts (elderly residents and young urban migrants) and economic roles (subsistence farmers and tourism entrepreneurs) to capture the unequal decision-making processes and varying economic capabilities that influence housing maintenance and modernization. These primary findings were triangulated with secondary data, including UNESCO World Heritage nomination documents, local construction guidelines and regional demographic statistics, to contextualize local architectural changes within the broader trends of rapid rural transformation and out-migration in China.

Result and discussion

The cultural and ecological significance of Jingmai's traditional homes: Multiple perspectives and lived experiences

The stilt houses of Jingmai Mountain represent a remarkable synthesis of cultural expression (Figure 2A, B & E), ecological adaptation and economic functionality that has evolved over centuries through the accumulated wisdom of the Bulang and Dai ethnic communities (Zhou et al. 2020). These bamboo and timber structures transcend their role as mere shelters to become living embodiments of a sophisticated worldview that seamlessly integrates spiritual beliefs, environmental stewardship and productive activities (Zou 2018) (Figure 2F). The architectural forms themselves serve as repositories of profound cultural meaning, with every structural element and decorative detail reflecting a deep understanding of local materials, environmental conditions and social organization. The distinctive decorative elements that adorn these homes – the sacred *one bud, two leaves* motifs revered by the Bulang people (Figure 2D) and the elegant ox-horn designs favoured by the Dai community (Figure 2C) – function as more than aesthetic choices, representing symbolic manifestations of the *tea ancestor* belief system that forms the spiritual and cultural foundation of these communities (Gao & Hu 2020).

The traditional architecture of Jingmai Mountain functions through specific technical adaptations to the humid mountain climate, employing indigenous construction techniques and local bio-materials to regulate the relationship between human habitation and natural systems (Figure 3A). For instance, the use of raised-stilt (Gan-lan) structures facilitates natural cross-ventilation and moisture reduction, while the selection of local timber and bamboo minimizes the carbon footprint and maintains thermal equilibrium within the dwellings (Shi et al. 2023; Xiong & Ruan 2024). The exclusive reliance on sustainable local materials – primarily bamboo harvested from managed groves and timber sourced from nearby forests – establishes a circular economy that minimizes environmental impact while supporting forest conservation efforts and maintaining biodiversity. This material selection reflects profound understanding of resource management principles developed through generations of experiential learning. The elevated stilt house design represents a masterful example of climate-responsive architecture, providing natural ventilation systems that moderate indoor temperatures, facilitate air circulation and protect inhabitants from seasonal flooding while reducing dependence on energy-intensive mechanical systems (Bai et al. 2020; Zhou et al. 2020).

Most significantly, these traditional homes function as integral components of Jingmai's tea production system, with their second-floor platforms serving as specialized spaces for tea drying, processing and storage activities that link architectural design directly to the community's primary economic foundation (Chen & Hu 2024; Gao et al. 2024). This functional integration demonstrates how traditional building practices evolved to support local livelihoods while maintaining cultural authenticity, creating built environments that serve multiple purposes simultaneously without compromising efficiency or cultural meaning. The homes operate as both residential spaces and productive infrastructure, embodying a holistic approach to community development that successfully integrates social, economic and environmental considerations. This multifunctional design philosophy reflects traditional knowledge systems that understood buildings not as isolated objects but as components of larger ecological and social systems, creating architectural solutions that enhanced community resilience while preserving cultural identity and environmental sustainability.

Contemporary challenges: Cultural change, rural-urban migration and architectural transformation in a twenty-first-century context

The preservation of Jingmai's traditional architectural heritage faces unprecedented challenges in the contemporary era, as multiple interconnected forces threaten to erode the cultural foundations that have sustained these communities for over a millennium. The transition from traditional bamboo and timber materials to concrete structures represents a significant structural shift within the cultural landscape. Driven by modernization processes and local aspirations for increased structural durability and reduced maintenance costs, this material substitution reflects a negotiation between heritage continuity and contemporary living standards. However, such transitions can alter the historical character of the settlement and reconfigure the symbolic relationships between inhabitants and their architectural heritage (Li et al. 2023a). While

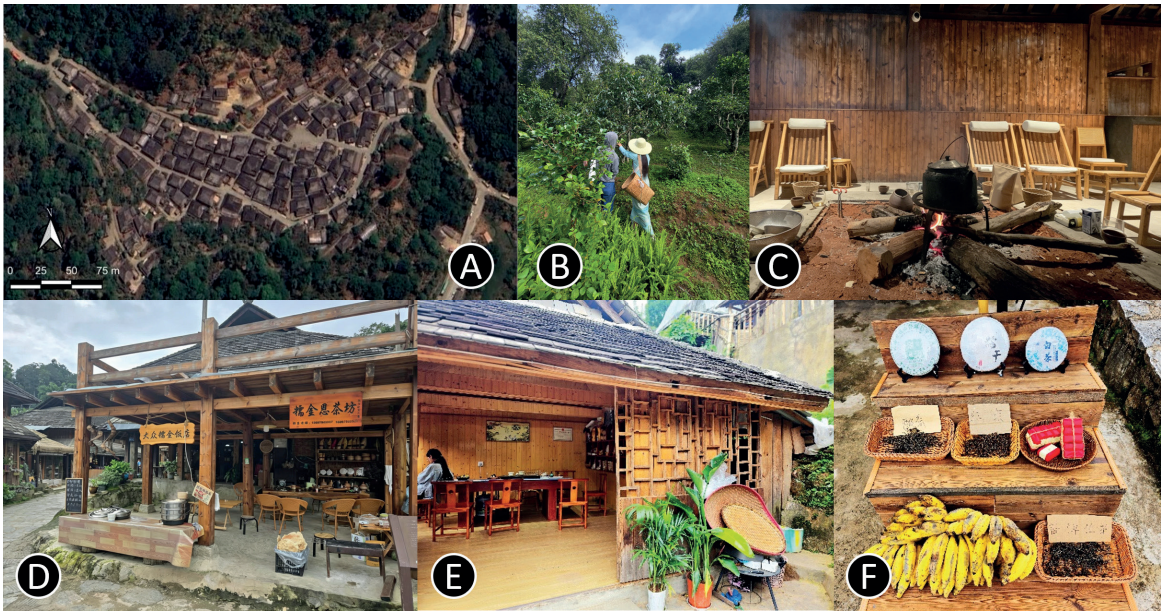


Figure 3 – Ecotourism in Jingmai Mountain. The traditional layout and wooden architectural complex of Nuogan Village in Jingmai Mountain reflect a harmonious integration with the surrounding ancient tea forests (A). In the ancient tea garden of Dapingzhang, tourists can participate in traditional tea-picking activities, gaining hands-on experience of local heritage (B). Inside a Dai-style wooden house, a huotang (fire pit) serves as a cultural hub where visitors engage in tea boiling, warm themselves by the fire and join in communal gatherings (C). In another corner of the village traditional snacks are for sale, showcasing the continuity of local culinary customs (D). In another corner of the village, locals are seen selling traditional snacks at their storefronts, showcasing the continuity of local culinary customs. (E), while local products such as bananas, Pu'er tea and mushrooms are also displayed and sold, contributing to the community's livelihood (F). © all pictures Chunping Xie

concrete construction may offer certain practical advantages in terms of structural longevity and weather resistance, it lacks entirely the profound cultural significance embedded in traditional materials and construction techniques, creating buildings that function as mere shelters rather than repositories of cultural meaning and identity (Korde et al. 2025). Moreover, the environmental impacts associated with concrete production and construction – including carbon emissions, resource depletion and landscape disruption – stand in stark contrast to the sustainable practices that traditional building methods successfully maintained for centuries without compromising ecological integrity. It is important to acknowledge, however, that residents' choices regarding building materials reflect complex calculations that preservation frameworks must take seriously. Interviews with households that have adopted concrete construction reveal practical considerations: reduced maintenance labour particularly important for aging residents or families with members working in distant cities; improved weather resistance in the context of increasingly unpredictable climate patterns; and longer structural lifespans that reduce long-term housing costs. Some residents explicitly articulate that concrete construction represents not a rejection of cultural heritage but rather a pursuit of housing security comparable to that available in urban areas. These perspectives suggest that effective preservation strategies must engage honestly with the economic and practical dimensions of housing choices rather than assuming that cultural values alone will motivate maintenance of traditional materials (Bahru et al. 2012; Alsheikh Mahmoud et al. 2024). This transformation highlights the need to consider how preservation approaches engage with residents' agency in housing decisions. It requires an analysis of the conditions that influence the economic viability and practical sustainability of traditional construction for local inhabitants. By examining these dynamics, preservation strategies can better account for the socio-economic motivations of those who choose to maintain or adapt traditional architectural forms within the modernizing landscape.

The adoption of modern building materials and construction techniques represents more than a simple technological shift; it constitutes a fundamental erosion of the authenticity that forms the conceptual and practical foundation of Jingmai's World Heritage designation and cultural significance. The daily experience of inhabiting traditional homes contributes to cultural continuity through sensory engagement and embodied knowledge that modern structures cannot replicate, as the distinctive sounds, textures, thermal properties and atmospheric qualities of bamboo and timber construction form integral components of the cultural memory that shapes ethnic identity and community belonging (Huang & Qin 2023). Yet it is crucial to recognize that the significance of these architectural forms is not uniformly experienced across the community. Field observations reveal that interpretations

of traditional architecture vary considerably among different demographic groups. Elderly Bulang and Dai residents often emphasize the spiritual and ancestral connections embodied in structural details (Xiong & Ruan 2024; Zhang & Xie 2024), while younger community members, particularly those with urban educational experiences, may appreciate these aesthetic and cultural values while simultaneously prioritizing practical housing considerations such as maintenance requirements, weather resistance and compatibility with modern amenities (Huang & Qin 2023; Zhang et al. 2024). Women and men may also relate differently to these spaces, given traditional gender divisions in domestic labour and building maintenance responsibilities. These diverse perspectives remind us that *community values* regarding traditional architecture cannot be assumed as monolithic but must be understood through careful attention to the varied positions and priorities of different community members.

The migration of rural populations to urban centres presents what may constitute the most significant long-term threat to Jingmai's traditional architecture, as demographic shifts fundamentally alter the human foundation upon which architectural preservation depends (Li et al. 2023a; Wang & Zakaria 2025). As younger generations increasingly seek educational opportunities, employment prospects and lifestyle amenities available in urban centres, traditional homes are progressively abandoned or left with inadequate maintenance and care, creating a deteriorating cycle where declining rural populations reduce the economic viability and social vitality of traditional communities. The mountainous terrain that contributes significantly to Jingmai's scenic beauty, ecological diversity and cultural distinctiveness simultaneously presents substantial challenges for modern infrastructure development, making urban alternatives increasingly attractive to young people who perceive rural life as limiting their personal and professional opportunities. The geographic isolation that historically protected traditional culture from external influences now functions as a barrier to economic development and social connection (Xu et al. 2005), creating fundamental tensions between heritage preservation objectives and community sustainability needs that require careful navigation and innovative solutions.

The reluctance of younger generations to remain in remote villages or return after urban education experiences threatens the critical process of intergenerational knowledge transmission that sustains both traditional building techniques and the broader cultural practices that give meaning to architectural heritage (Rao & Ye 2016; Mohabir et al. 2017). The specialized knowledge required to construct, maintain and repair bamboo and timber homes represents accumulated wisdom developed through centuries of experiential learning and refinement, encompassing not only technical skills, but also a deep understanding of material properties, environmental conditions and cultural protocols that cannot adequately be documented or preserved through written records alone. As elderly craftspeople age without successfully training successors in traditional construction methods, this irreplaceable indigenous knowledge faces genuine extinction, representing a cultural loss that would be impossible to recover once the chain of practical transmission is broken (Yuan 2011). The *tea ancestor* belief system and associated cultural practices that provide spiritual and social meaning to traditional architecture face similar risks as younger generations, influenced by modern educational curricula and urban lifestyle aspirations (Zheng 2016; Gao et al. 2024), demonstrate declining interest in traditional worldviews and customary practices that their elders consider fundamental to community identity and ecological stewardship.

Integrating traditional architectural heritage into mountain socio-ecological systems: Drivers of change and pathways for sustainable rural transformation

The functional integration of Jingmai's traditional bamboo and timber homes within the local economy extends beyond heritage conservation to encompass the dynamics of sustainable economic development and cultural revitalization (Fan & Deng 2022) (Figure 3A). As central components of the cultural landscape, these stilt structures act as primary drivers for ecotourists, where their placement within working tea gardens facilitates unique visitor experiences and diversified economic opportunities for local communities (Figure 3B & C). Beyond direct aesthetic appeal, these dwellings serve as nodes for international attention through contemporary media, supporting a tourism model that integrates hospitality, guiding and cultural interpretation services (Figure 3D & F). Empirical observations suggest that the adaptive reuse of traditional structures as eco-lodges can provide economic incentives for the younger generation, potentially mitigating the demographic challenges associated with rural-to-urban migration.

The successful implementation of preservation pathways depends on collaborative governance structures that integrate local communities, government agencies and international partners (Zhang & Chen 2023; Liu 2025). Educational initiatives emphasize the environmental knowledge embedded in traditional building practices (Seerangan & Ravi 2023), framing heritage preservation as relevant to contemporary sustainability challenges. Spatial planning and infrastructure investments aim to enhance village life while minimizing the visual impact on traditional architecture. These coordinated efforts address the socio-economic drivers of rural-urban migration, ensuring that Jingmai's architectural heritage remains a functional component of contemporary mountain life.

Navigating diverse stakeholder interests in heritage-based development

The transition toward heritage-based development reveals that heritage designation creates different opportunities and constraints for different community members (Kaur et al. 2025). Empirical evidence from Jingmai suggests that households located along primary tourist routes or near scenic sites typically exhibit higher rates of house-to-guesthouses conversion, while those in peripheral locations face more limited participation options (Goodwin & Roe 2001; Shi et al. 2023). Furthermore, access to benefits is often mediated by capital for facility improvements and language skills, which can lead to socio-economic stratification within the community. These disparities highlight the importance of mechanisms (Fonseca & Ramos 2012) – such as community revenue-sharing and targeted training programmes – to ensure that preservation outcomes are distributed broadly across the community.

Furthermore, different generations often have different stakes in architectural outcomes. Elderly residents frequently prioritize cultural continuity and spiritual connections to ancestral homes (Chua et al. 2019), while younger community members may weigh cultural heritage against economic mobility and access to modern infrastructure (Xiao et al. 2021). Preservation frameworks, therefore, must navigate these divergent perspectives – enabling young people to maintain connections with traditional practices while also pursuing contemporary economic opportunities. This ensures that heritage conservation does not become a barrier to improved livelihoods and infrastructure development. Similarly, the distinct cultural traditions of the Bulang and Dai communities require flexible preservation approaches that accommodate different relationships to architectural heritage. Community-engaged planning processes that create space for diverse voices – across ethnic identities, generations, genders and economic positions – are essential for developing pathways that genuinely serve the varied interests present within Jingmai's population (Liu 2025).

Conclusion

This study demonstrates that the architectural heritage of Jingmai Mountain is a dynamic component of a mountain socio-ecological system, whose continuity depends on navigating the complex tensions between heritage conservation and modernization. The transition of building materials and the demographic shift caused by rural-urban migration highlight that preservation is not merely a technical task, but also a multifaceted social negotiation involving diverse community stakeholders with varying economic capabilities. Therefore, effective preservation strategies must move beyond static artifact protection toward flexible, community-engaged frameworks that align traditional building practices with the evolving economic aspirations of local inhabitants. By addressing the socio-economic drivers of migration and incentivizing the adaptive reuse of dwellings, heritage management can support vibrant, economically viable communities. Looking forward, the *Jingmai model* suggests that the survival of global mountain heritage will increasingly rely on the hybridization of indigenous technical knowledge with modern sustainability standards. This approach ensures that cultural landscapes remain functional, resilient and relevant to the contemporary lived experiences of the communities that sustain them.

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Regenerative Tourism and its Importance for Conservation Areas and Regional Nature Parks

Sarah Balet & Nadja Urfer

Keywords: regenerative tourism, sustainability, natural areas, resilience

Abstract

Tourism in sensitive natural areas creates both benefits and pressures, prompting growing recognition that traditional sustainability is no longer sufficient. Regenerative tourism has emerged as a transformative paradigm that seeks to restore and enhance socioecological systems through systems thinking, ecological worldviews and community centered practices. This article clarifies the conceptual foundations of regenerative tourism and highlights its relevance for conservation areas and regional nature parks, where ecological fragility and societal expectations converge. Drawing on a collaboration between the Swiss Parks Network and the Institute of Tourism of HES-SO Valais–Wallis, it examines how regenerative principles resonate with the Swiss parks' values and principles. The analysis shows strong alignment but identifies implementation challenges, including limited experience and missing supportive structures. As model regions for sustainable development, the Swiss parks are well positioned to pioneer regenerative tourism and encourage its wider adoption by tourism partners.

Introduction

Tourism in conservation areas and nature parks has long been characterized by a fundamental tension. On the one hand, it can generate economic value for peripheral regions, support local employment and raise public awareness of biodiversity and conservation objectives. On the other hand, tourism increasingly contributes to ecological degradation, resource overuse, social conflict and climate change (Duarte et al. 2024). Following the COVID-19 pandemic, Swiss parks experienced a marked increase in visitor numbers (Müller 2022), reinforcing long-standing challenges related to overcrowding, traffic and ecosystem disturbance.

Traditional sustainability-oriented tourism strategies have largely focused on mitigating negative impacts through efficiency measures and visitor management. While such approaches remain necessary, they appear insufficient in the face of accelerating biodiversity loss, climate change and growing social tensions between residents and visitors. Against this backdrop, regenerative tourism has gained prominence as an alternative paradigm that claims to move beyond harm reduction towards actively restoring socioecological systems (Dredge 2022). However, its ability to respond to concrete tourism-related challenges, particularly in vulnerable landscapes, requires critical examination.

This article introduces regenerative tourism, situates it in relation to sustainability-oriented approaches and examines its relevance for conservation areas and nature parks, with a particular focus on the Swiss context. It also assesses both the opportunities and the limits of applying regenerative principles to tourism management in those areas.

What is regenerative tourism?

Regenerative tourism builds on the regenerative theory emerging from fields such as agriculture, urban planning and ecological economics (Bellato et al. 2023). Unlike traditional sustainability approaches that focus primarily on minimizing harm or managing carrying capacity, the regenerative one seeks to produce *net-positive* outcomes for ecological integrity, community wellbeing and socioecological resilience. This approach marks a fundamental conceptual shift: tourism is reframed not as an end in itself but as a mechanism that supports the flourishing of ecosystems and local communities (Bellato et al. 2025). It emphasizes quality over quantity, collaboration rather than competition and reciprocity instead of extractive value creation. It challenges the assumption that continuous growth is inherently desirable and calls for place-based design tailored to local ecological and cultural contexts (Dredge 2022).

Yet, despite its conceptual appeal, regenerative tourism faces considerable challenges. Questions remain regarding how to define system boundaries, how to measure *net-positive* outcomes, and how to address tourism's structural dependence on mobility and resource consumption. The growing popularity of regenerative tourism brings a heightened risk of *greenwashing*. Critics caution that without clearer definitions, regulatory bodies and agreed-upon metrics, regenerative tourism risks becoming a vague umbrella concept, vulnerable to misinterpretation and instrumentalization for marketing purposes (Gilbert-Jones et al. 2024).

Distinguishing genuine regenerative practices therefore requires transparency in intent, process and outcomes. While the concept rejects standardized metrics, the methodology for defining and monitoring impacts should be explicit. Emerging frameworks suggest assessing regenerative impact across interconnected pillars, including ecological outcomes (biodiversity,

climate mitigation); social and cultural integrity; fair economic distribution; visitor engagement and behavior change; compliance and monitoring; innovation; and community wellbeing (Gilbert-Jones et al. 2024). A holistic, systems-based approach, rather than isolated indicators, is essential for avoiding reductionist interpretations of regeneration and capturing a place's specificities and unique challenges.

Tourism pressures in sensitive areas: moving from efficiency to resilience

The relationship between tourism and nature is inherently ambivalent. Pristine landscapes constitute the primary *capital* of nature-based tourism, serving as a region's unique selling proposition. At the same time, their growing popularity generates significant ecological pressure: high visitor numbers contribute to soil erosion, wildlife disturbance, vegetation loss and waste accumulation, particularly when tourists move off marked trails or engage in unregulated activities (Felber 2020). Infrastructure development, traffic congestion and reliance on private vehicles further increase environmental stress and carbon emissions. Social and economic impacts are equally significant yet often less visible. Excessive tourism may intensify conflicts between visitors and residents, for example when recreational activities interfere with agricultural practices or when new tourism infrastructure conflicts with conservation objectives (Felber 2020). Cultural commodification and the unequal distribution of benefits can undermine local cohesion, while strong dependence on tourism increases regional vulnerability to external shocks, as illustrated during the COVID19 pandemic (IUCN 2025).

In many conservation areas and nature parks, including Swiss parks, sustainable tourism has promoted practices focused on impact reduction, visitor management and efficiency (IUCN 2025). However, these approaches frequently remain rooted in an industrial worldview that separates humans from nature and prioritizes optimization over transformation (Dredge 2022). By seeking to manage impacts rather than interrogate tourism's role within socioecological systems, such models may alleviate immediate pressures while leaving underlying causes of environmental degradation and social tensions unresolved. This limitation is particularly problematic given that many conservation areas face a significant ecological debt resulting from historical land-use practices, long-term biodiversity decline and cumulative visitor pressures (IUCN 2025).

The potential of regenerative tourism for sensitive areas

Regenerative tourism proposes addressing current challenges by shifting from minimizing damage to actively restoring ecological and social systems. It could help mobilize tourism actors, revenues and visitor engagement towards restoration efforts such as habitat regeneration, rewilding, invasive species management or carbon positive infrastructure (Duarte et al. 2024). For instance, tourists in Seychelles, accompanied by scientists, transplant corals while scuba diving. They transition from a contemplative activity to a concrete commitment to coral reef restoration (Maczko 2025). In Amsterdam, the company Plastic Whale combines canal tours with waste cleanup (MacEacheran 2020). Visitors are considered as participants who contribute to the health of the places they visit, rather than passive consumers. Beyond ecological benefits, regenerative tourism could strengthen social resilience by embedding local communities as costewards of protected areas. Participatory governance and communityled initiatives reinforce cultural knowledge, social cohesion and shared responsibility for conservation outcomes (Bellato et al. 2025).

For tourism plausibly to deliver *net-positive* outcomes, a fundamental shift in intent and governance is required. Regeneration demands a move from defensive impact management to proactive place-based design, grounded in local knowledge and collaborative decision-making. This includes identifying which resources must be protected or restored, which activities are compatible with ecosystem capacities and which forms of tourism may need to be limited or avoided (Bellato et al. 2023).

Key conditions include treating destinations as living systems; fostering reciprocal relationships between visitors, communities and ecosystems; and building regenerative capacity through restoration, learning and adaptive management (Bellato et al. 2023). Crucially, regeneration cannot be imposed through expert-led solutions alone; it depends on bottom-up processes and the empowerment of local actors (Dredge 2022). Without such conditions, claims of *net-positive* tourism risk remaining merely aspirational.

Interest from the Swiss Parks Network

Swiss parks position themselves as model regions for sustainable development and explicitly acknowledge both the opportunities and the pressures associated with tourism. Their Tourism Vision 2030 aims to ensure that tourism generates positive outcomes for residents, visitors and regional economies while preserving and enhancing natural and cultural landscapes (Swiss Parks Network n.d. b). An analysis conducted in December 2024 with HES-SO Valais–Wallis demonstrates strong alignment between regenerative principles and the parks' values, particularly regarding systemic thinking, inclusiveness and place-based approaches (HES-SO Valais-Wallis 2025). Those findings were discussed with the parks' tourism managers and representatives of regional tourism organizations, confirming strong alignment between regenerative principles and the parks' seven core values (Swiss Parks Network n.d. a).

At the same time, significant implementation barriers persist. These include limited practical experience with regenerative models, a lack of supportive policy frameworks and the absence of demonstrable outcomes that could convince tourism partners to engage more deeply. To counteract this, the Regional Nature Park PfynFinges has launched a pilot project in collaboration with HES-SO Valais-Wallis to develop a regenerative tourism offer. According to Sophie Michaud, Head of Sustainability, Products and Tourism, "*this project enables us to engage in dialogue with our partners in the tourism industry on sustainability issues and strengthen our cooperation. It stimulates our creativity and allows us to break new ground.*" Such initiatives represent important testing grounds for strengthening the concept, as well as highlighting its shortcomings.

Conclusion and future directions

Regenerative tourism proposes a shift toward an ecological worldview in which destinations are understood as complex socioecological systems. Rather than asking how tourism can be made *less harmful*, regenerative approaches question whether, where and under what conditions tourism should occur at all. From a regenerative perspective, resilience implies not only preserving existing conditions, but also actively restoring degraded ecosystems and rebuilding ecological functions, while strengthening local capacities to adapt to future shocks. Regeneration does not replace sustainability but extends it along a spectrum from efficiency to resilience and renewal.

Regenerative tourism offers a promising yet demanding pathway for conservation areas and regional nature parks seeking to respond to mounting ecological and social pressures. However, its successful application depends on the robustness of the concept. It implies the necessity to define tourism's role in natural areas, to engage critically with both the potential and the limitations of the regenerative concept and to develop adequate metrics to measure outcomes towards resilient socioecological systems.

Looking ahead, the Swiss Parks Network intends to advance the development of the currently missing foundations necessary for practical implementation by working closely with academic partners and park managers to test new approaches within natural contexts. The resulting insights will be shared with the wider industry and are intended to contribute to a form of tourism development that is fit for future generations. *Should you have any interest in further investigating this topic* by either participating in the task force on regenerative tourism in parks or collaborating in future research, *please do not hesitate to contact us.*

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The Restoration of Aquatic Ecosystems in the Alps and Pyrenees: A Case Study from the LIFE RESQUE ALPYR Project

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Keywords: High Mountain lakes, non-native fish eradication, mires and peatlands, Natura 2000, amphibians, wet meadow management, mountain conservation

Abstract

High mountain aquatic and semi-aquatic ecosystems of the alpine biogeographical region harbour specialized biota, yet they are increasingly being degraded by non-native fish introductions, livestock pressure, afforestation and the abandonment of traditional wet meadow management. The LIFE RESQUE ALPYR project (2022–26) implements coordinated restoration actions across four Natura 2000 sites in the Pyrenees and the Alps, targeting eleven habitat types and several threatened vertebrate species. Building on prior LIFE initiatives in both mountain ranges, LIFE RESQUE ALPYR develops and tests replicable protocols for invasive fish eradication in lakes of varying sizes, livestock exclusion from sensitive waters and mires, clear-cutting and revegetation on afforested mires and the re-establishment of mowing in wet meadows. Here we present the project's ecological rationale, study areas, objectives and methods, together with the expected outcomes and lessons learned to support transferability to other mountain protected areas. This approach integrates robust ecological monitoring and stakeholder engagement to ensure long-term biodiversity gains and to reconcile traditional land-use practices with modern conservation priorities. Evidence from comparable Alpine and Pyrenean systems shows that amphibian and aquatic invertebrate communities can recover rapidly following fish removal, while mire restoration and appropriate meadow management accelerate vegetation and trophic recovery, producing cascading benefits for riparian and semi-aquatic insectivores. Quantified outcomes include the complete removal of non-native fish from 22 lakes (55.4 ha); the reoligotrophication of 10 lakes; the restoration of ≥3 ha of wet meadows and ≥8–10 ha of mires by means of grazing-exclusion and afforestation-removal actions; and the development of operational protocols designed for replication in European mountain regions.

Introduction and conservation context

High-mountain aquatic and semi-aquatic ecosystems (glacial lakes, peat bogs and mires, wet grasslands and seasonally flooded meadows) are characterized by harsh climates, short growing seasons and high levels of specialization and endemism (Schmitt 2009; Pironon et al. 2022). Although limited in extent, these habitats include several priority habitat types listed under the EU Habitats Directive, together with specialized plant communities such as *Sphagnum*-dominated peatland flora and wet-meadow species of high conservation value. They support unique assemblages ranging from invertebrates and amphibians to semi-aquatic mammals and insectivorous bats, many of which are also protected under European legislation.

During recent decades, the ecological integrity of these systems has been increasingly compromised across Europe. Historically fishless alpine lakes have been widely stocked with predatory fish for recreational angling (Tiberti et al. 2014b; Ventura et al. 2017), while land-use changes have intensified nutrient inputs (Tiberti et al. 2014a) and disrupted natural hydrological regimes (Rossi et al. 2024). In both the Pyrenees and the Alps, introductions of trout (*Salmo trutta*, *Oncorhynchus mykiss*, *Salvelinus alpinus*, *Salvelinus fontinalis*) and minnows (*Phoxinus* spp.) have caused amphibian extirpations (Tiberti & von Hardenberg 2012; Miró et al. 2018); altered littoral (Buchaca et al. 2022; Osorio et al. 2022) and pelagic (Tiberti et al. 2014b; Sabás et al. 2019) food webs; and reduced insect emergence (Tiberti et al. 2016) and trophic subsidies from lakes to terrestrial ecosystems (Bello et al. 2024).

Mires in these mountain regions are also affected by livestock overgrazing, which increases nutrient load, disturbs peat soils (both by compaction and pugging) and alters diatom and bryophyte assemblages, driving systems toward hydrological instability (Rossi et al. 2024). Studies from European mountains show clear compositional shifts in grazed mires, with resilience determined by pH and bryophyte cover, and increases in eutraphentic taxa under intense pressure (Gonzalez-Saldias et al. 2025). At the same time, afforestation of subalpine mires lowers water tables and increases shading, promoting transitions to more generalist vegetation. To mitigate this problem, targeted tree removal combined with active revegetation accelerates the recovery of peat-forming plant communities (Hedberg et al. 2012); meta-analyses show that enhanced restoration consistently outperforms passive approaches (Allan et al. 2024). Abandonment of traditional mowing adds another layer of pressure on wet meadows, where lack of management favours competitive dominant graminoids and reduces species richness. Long-term experiments and synthesis studies indicate that well-timed, low-intensity mowing can counteract successional homogenization, although responses vary depending on hydrological conditions (Hajková et al. 2022).

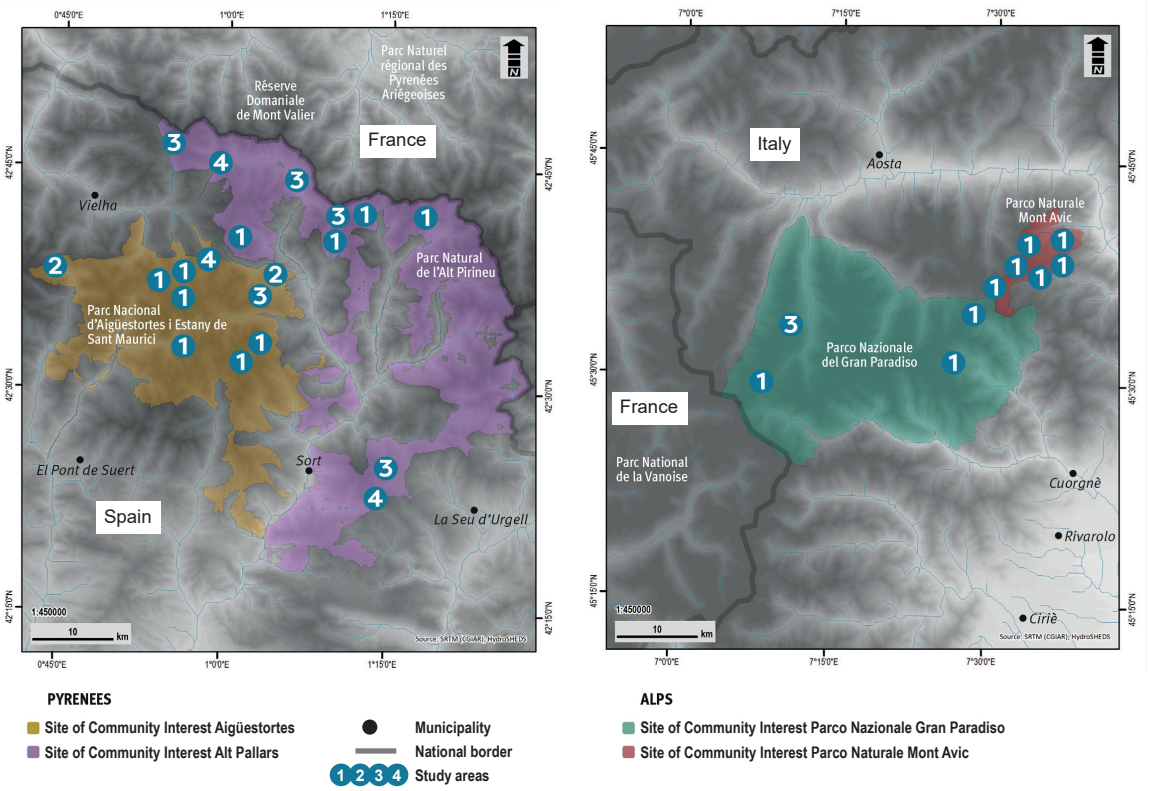


Figure 1 – Map of the study area with conservation actions indicated by numbers: 1) Restoring the natural state of some lakes through the elimination of non-native fish species; 2) Selective mowing of meadows and neighbouring mires; 3) Livestock grazing management; 4) Conservation improvement of mires by selective tree clearcutting. Source: SRTM (CGIAR); HydroSHEDS

Taken together, these interacting threats underscore the need for integrated, site-specific restoration strategies that simultaneously address trophic disruption, hydrological alteration and land-use change. This need has been progressively tackled through successive LIFE projects. The LIFE+ BIOAQUAE project (LIFE11 BIO/IT/000020) marked a major milestone by carrying out the first successful eradication of salmonids from high-mountain lakes in Europe. Building on this achievement, LIFE+ LimnoPirineus (LIFE13 NAT/ES/001210) (Carrillo et al. 2020) accomplished the first complete removal of non-native minnows from small lakes in the Pyrenees. In addition to developing and validating effective protocols for eliminating invasive fish in small alpine lakes, LIFE+ LimnoPirineus implemented a broad suite of habitat restoration actions, including peatland and wet-meadow improvements, recovery of priority habitats and targeted measures for specialist flora. Together, these actions provided a solid proof of concept for integrated restoration approaches in the Pyrenees. As a result of this coordinated work, native amphibian communities showed rapid recovery, and the ecological structure and functioning of high-mountain mires were substantially enhanced. Building upon these advances, LIFE RESQUE ALPYR (LIFE20 NAT/ES/000369) (Centre d'Estudis Avançats de Blanes 2022) constitutes the crucial phase of scaling and validating these methods at a broader biogeographical scale. The project extends this approach across both the Pyrenees and the Alps and tackles more complex challenges, particularly the eradication of invasive fish from larger lakes, thereby demonstrating its wider applicability across Europe.

Study areas and target taxa

LIFE RESQUE ALPYR operates across four Natura 2000 sites from the Pyrenees and the Alps: the Aigüestortes i Estany de Sant Maurici National Park (PNAESM) with SCI Aigüestortes (ES0000022), the Alt Pirineu Natural Park (PNAP) with SCI Alt Pallars (ES5130003), the Gran Paradiso National Park (IT1201000) and the Mont Avic Natural Park (IT1202000) (Figure 1). Baseline surveys across these areas revealed high incidences of invasive fish in high mountain lakes and widespread grazing impacts in mires, alongside accelerating forest encroachment threatening subalpine mires.

In the Pyrenees, introduced fish are now present in approximately 70% of lakes within Aigüestortes and 35% within Alt Pallars (Miró & Ventura 2013, 2015). In the Alps, 89% of lakes in Mont Avic and 29% in Gran Paradiso are affected. These introductions have caused local extirpations of amphibians and declines in aquatic invertebrate communities, with cascading effects on semi-aquatic mammals that depend on emergent aquatic insects for foraging (Figure 2).

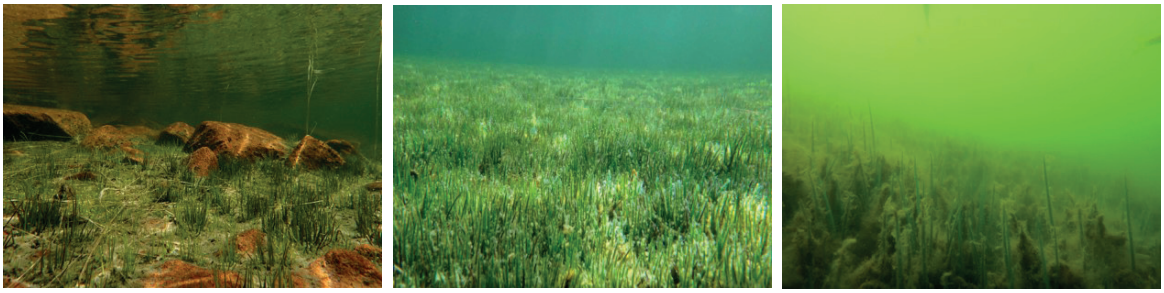


Figure 2 – Photographs showing the effects of fish presence on water transparency and the presence of microalgae. From left to right: natural Lake without fish; lake with trout and minnow; lake with minnow. © Kike Ballesteros

Mires in the project area face additional pressures from livestock overgrazing. In Aigüestortes and Alt Pallars, 80% of mires are grazed and 20% are overgrazed, leading to plant mechanical disturbance, soil alterations through trampling and increased nutrient inputs that, taken together, compromise habitat quality. Simultaneously, afforestation by *Pinus uncinata* and other tree species lowers water tables, increases shading and shifts peatland communities toward generalist species. Approximately 30% of subalpine mires in the Spanish sites are currently affected by forest encroachment. The parallel decline in traditional mowing practices further contributes to the homogenization of wet meadows, favouring dominant graminoids and facilitating additional encroachment.

The project targets eleven Annex I habitat types, including priority HCIs 4020*, 6230*, 7110*, 91D0* and 7220*, covering alpine lakes (3110, 3130), wet grasslands and meadows (6410, 6520) and minerotrophic and ombrotrophic mires (7140, 7230). Focal vertebrates include amphibians such as *Rana temporaria*, *Calotriton asper*, *Alytes obstetricans* and *Alytes almogavarii*; the semi-aquatic mammal *Galemys pyrenaicus*; and seven species of insectivorous bats, including *Rhinolophus hipposideros*, *Plecotus macrobullaris* and *Barbastella barbastellus*. Their foraging behaviour can depend heavily on aquatic insect emergence, with evidence from European lakes and riparian systems showing that bat activity peaks coincide with emergence dynamics and aerial insect flux from water bodies (Salvarina et al. 2018).



Figure 3 – Main methods used for non-native fish eradication in high mountain lakes. Clockwise from top left: fykenetting, with nets deployed along littoral zones to capture minnows larger than ~30 mm; electrofishing, allowing active capture of both minnows and salmonids of all sizes in littoral areas and in associated inlet and outlet stream sections; gillnetting, deployed all over the lake for both minnows and salmonids; intensive rod-angling: complementary fish removal method to reduce the initial density of adult salmonids. © Fykenetting and Electrofishing by Sorelló Estudis al Medi Aquàtic. Rodangling and Gillnetting by Stefano Brighenti.



Figure 4 – Rotenone application in Lake Manhèra (SCI Aigüestortes, Val d'Aran). © Marc Ventura



Figure 5 – Temporary fence (August to October) at Estanyeres de Son (PNAESM, within the park). Livestock exclusion fences promote the recovery of vegetation and flowering of plants, allowing them to recolonize degraded areas. © Eulàlia Pladevall

Objectives and working hypotheses

The overarching objective is to restore the ecological function of high mountain lakes and mires, re-establish amphibian metapopulation connectivity and improve the conservation status of semi-aquatic mammals and insectivorous bats by removing alien fish, reducing nutrient and trampling pressures, reinstating wet meadow management and reversing afforestation in mires. The project also aims to generate replicable protocols for mechanical and chemical fish eradication, livestock management and mowing and mire forest control, and to upscale results via a European expert network and practitioner guidelines.

Conservation actions and methods

Invasive fish eradication in High Mountain Lakes

We designed eradication campaigns tailored to lake size, bathymetry and habitat complexity. Following pre-treatment baseline surveys of amphibians, macroinvertebrates, zooplankton and key physico-chemical indicators, fish removal was carried out through intensive, multi-year, site-specific operations combining gill-netting across depth strata, fykenetting, electrofishing and targeted rod angling, with effort scaled to bathymetry and structural complexity (Figure 3). In total, 22 lakes across both mountain ranges (Figure 1) are undergoing treatment. Field effort will be adjusted adaptively, increasing if fish reduction is below 90% after the second year, applying criteria established in previous LIFE projects. This approach maximizes cost-efficiency, extends eradication feasibility to medium and large lakes and generates transferable decision rules and effort–response curves to guide future replication.

Where mechanical methods are infeasible, the project tests a rigorously controlled eradication protocol using rotenone, a biodegradable piscicide. This approach was used in three Pyrenean lakes with minimal outflow and severe minnow impacts: Tres Estanys del Mig (3.7 ha), Tres Estanys de Baix (2.8 ha) and Manhèra (1.5 ha) (Figure 4). Treatments use CFT Legumine® (3.3% rotenone) under the supervision of the Norwegian Veterinary Institute and are timed to minimize side effects on non-target taxa; rotenone decay is tracked via GC-MS (Prats et al. 2024) to confirm rapid dissipation. The objectives are the permanent removal of *Phoxinus* spp. and the rapid recovery of native communities, while establishing an EU relevant safety blueprint for piscicide use in sensitive mountain contexts.

Selective mowing of wet meadows

Traditional mowing has been reinstated in the two subalpine sites of Aigüestortes and Pleta de Molières i Planes de Son, on a combined 3 ha, with ~80% of the area mown each summer and ~20% retained as controls. The action targets recovery of HCIs 6410 and 6520 and also benefits associated mires and wet heaths (4020*, 7230) through increased structural heterogeneity and reduced graminoid dominance (locally, tree and shrub encroachment is also reduced).

Livestock management and assisted plant migration

In six mire systems across Spain (Rubió, Sartari, Font de la Tosca, Plan deth Horn, Estanyeres) and Italy (the Djouan area), the project deploys permanent and seasonal fencing (typically 0.2–1.0 ha per enclosure) to halt trampling and eutrophication, supplements this with assisted transplants of mire specialists in Spanish sites (0.5–2% of area, 3–10 species) and installs minor trail rerouting to maintain pastoral activity while protecting sensitive zones (Figure 5).

Selective tree removal in mires

At Locampo, Parros and Pla Muntaner, ~6 ha of mire systems have been cleared of encroaching *Pinus uncinata* following baseline hydrology and vegetation assessments, with partial retention at Locampo and Parros and near total removal in Pla Muntaner to re-





Figure 6 – Training course for professionals specializing in the knowledge and dissemination of the Alt Pirineu Natural Park's values (SCI Alt Pallars). © Top: Alt Pirineu Natural Park; bottom Marta Mora



Figure 7 – Project presentation and educational activity in the Forum of Green Schools (Centre de Fauna Pont de Suert, Alta Ribagorça). © Associació la Sorellona



Figure 8 – Intensive angling sessions (Lake Miserino, SCI Gran Paradiso National Park) have been used to engage anglers as key stakeholders and promote ecological awareness. Angling in mountain lakes is both a primary pathway for fish invasions and a popular recreational activity outside protected areas. Addressing this potentially conflicting context probably represents the most challenging communication objective of the entire project. © Stefano Brighenti

store water tables and light regimes that favour peat forming communities. Citizen participation complements professional staff to strengthen social acceptance and awareness.

Community engagement and dissemination

Stakeholder workshops, field days and materials shared with protected-area managers and schools frame restoration as a partnership. This social process is essential where fish eradication or livestock exclusion could raise concerns; communicating robust ecological evidence and demonstrating rapid recovery helps sustain local support. Documented links between fish removal, increased amphibian and macroinvertebrate presence and improved foraging resources for terrestrial insectivores provide compelling narratives for broader biodiversity benefits (Figures 6, 7 and 8).

Monitoring, evaluation and expected outcomes

A comprehensive monitoring and evaluation framework sustains the project's ecological restoration goals while quantifying outcomes at biological, environmental and socio-economic scales (Figure 9). Nine dedicated monitoring actions assess rotenone decay until concentrations fall below analytical detection, and model fish-removal success in near real time using open-population removal models. Lake recovery is evaluated through standard surveys tracking amphibians, macroinvertebrates, macrophytes, phytoplankton and zooplankton and water transparency. Cross-ecosystem effects of fish removal are measured with automated bat acoustic recorders and non-invasive monitoring (e.g., environmental DNA) of semi-aquatic insectivores including *G. pyrenaicus*. Vegetation, bryophytes, butterflies, water-table levels and cryptic soil and moss-dwelling biodiversity are recorded in permanent plots in hay meadows, fenced mires and peatland areas following clear-cutting.

In parallel with ecological monitoring, surveys are conducted with citizens (400), university students (200) and key stakeholders (50–100, including natural area managers, scientific community, anglers, farmers, NGOs, etc.) to assess perceptions and potential conflicts regarding the conservation actions. All indicators feed into a dynamic LIFE KPI database updated until 2026 and maintained thereafter under the After-LIFE plan.

Expected outcomes include the complete eradication of alien fish from 22 lakes (55.4 ha) across the four SCIs, three treated with rotenone and 19 through mechanical control, reducing the proportion of invaded lakes. Reoligotrophication towards reference conditions is targeted in at least 10 lakes impacted by livestock or minnow-driven trophic shifts, with transparency, nutrients and chlorophyll monitored against pristine benchmarks. Habitat restoration totals ~3 ha of wet meadows at Aigüestortes, ~4 ha of fenced

peatlands in Spain and Italy, ~6 ha of selective deforestation in mires and ~150 m² of recovery in the petrifying spring at Font de la Tosca.

Rapid recolonization of treated lakes by amphibians is expected where nearby source populations persist, alongside the re-establishment of macroinvertebrate and zooplankton communities typical of fishless conditions. Increased insect emergence is anticipated to enhance foraging for bats and other insectivores. Project deliverables include technical guidelines for mechanical and chemical fish eradication, for grazing and mowing management and for mire forest control, as well as a monograph synthesizing all monitoring evidence to support replication in other regions.

Risk management and mitigation

Use of rotenone is restricted to three closed-basin lakes selected for minimal outflow and maximal ecological benefit; permissions were obtained from the competent authorities, and application is supervised by Europe's most experienced rotenone team to assure compliance and safety. Seasonal timing avoids sensitive life stages of non-target taxa, and degradation is chemically verified. Mechanical eradications adapt effort if reductions are <90% by year two. Fence maintenance is planned throughout the alpine season to address weather damage, and participatory engagement is used to limit the risk of sabotage. The budget includes a 5% buffer for inflation, with protected areas prepared to extend eradication for up to two years post-project if needed.

Replicability, innovation and socio-economic impact

RESQUE ALPYR's two major demonstration fronts are the first rigorous, monitored application of rotenone in EU high mountain lakes and the scaling of mechanical eradication to medium and large structurally complex lakes with explicit effort rules and eradication probability modelling. The project also pilots assisted plant migration in overgrazed mires and integrates molecular tools into routine monitoring to make biodiversity surveillance cost effective and transferable. With more than 1.5 million visitors a year across the four protected areas, open exhibitions, citizen science via the iNaturalist platform and a specialist network under action E.5 are expected to accelerate the diffusion of methods and policies such as fishing and live bait bans, which the partner parks already enforce as a precondition for durable outcomes. Job creation amounts to ~12 FTEs (full-time equivalent) during the project, with additional indirect benefits through local services and eco-tourism.



Figure 9 – Standard surveys of vegetation and macroinvertebrates in the areas under study. © Top: Eulàlia Pladevall; bottom: Marta Mora

Conclusions

LIFE RESQUE ALPYR illustrates how integrated restoration, combining non-native fish removal, hydrology-based peatland recovery and reinstatement of traditional wet-meadow management, can rebuild trophic structure and biodiversity in high-mountain aquatic systems. Evidence from the Pyrenees and the Alps demonstrates that these actions are feasible, ecologically effective and replicable, with rapid amphibian and invertebrate recovery after fish eradication and accelerated vegetation recovery under enhanced peatland practices. By coupling robust monitoring with stakeholder engagement, protected mountain areas across Europe can adopt and adapt this model to reverse degradation and secure long-term ecological integrity.

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Biodiversity in Jiugong Mountain National Natural Reserve, China

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Keywords: Jiugong mountain, biodiversity conservation, biological invasion, climate change, Subtropical zone

Abstract

Due to its special earth history, biodiversity and landscape, the Jiugong Mountain National Natural Reserve, located in the southeast of Hubei Province, is an important biodiversity hotspot in the central Yangtze River Basin. Based on our investigation, it contains rich flora and fauna, especially endangered plants and animals distributed in the Jiugong Mountain National Natural Reserve. Human disturbance, invasion by non-native species and small-size hydropower stations serious threaten local biodiversity and ecosystem function. We provide an overview of Jiugong Mountain's specialized endangered species (such as *Asarum campaniforum* and *Primula hubeiensis*), the threats they face and the protective conservation measures in place better to preserve biodiversity and ecosystem functions. The purpose of this study is to conserve biodiversity in highland areas, such as the central Yangtze River basin, by setting out practical knowledge and conservation measures.

Profile

Protected area

Jiugong Mountain National Natural Reserve

Mountain range

Jiugong mountain, China

Introduction

Mountainous regions cover less than 20% of the earth's terrestrial land surface (Rahbek et al. 2019), however, they support very high global biodiversity: about one third of total terrestrial biodiversity (Fjeldså et al. 2012; Badgley et al. 2017). Meanwhile, natural products from mountains, such as timber, food, medicine, freshwater and other biological resources provide important support for human well-being and sustainable development (Pender 2004; Payne et al. 2020). However, mountain areas are also sensitive to pressures, such as habitat fragmentation, human disturbance, biological invasion and climate change, which represent serious threats to global biodiversity, ecosystem structure and function and the sustainable development of human society (Jansky et al. 2002; Gong et al. 2019; Peng et al. 2021). Thus, more monitoring and research should be focused on highland regions in order better to protect natural resources in mountainous areas and achieve sustainable development (McCain & Colwell 2011; Zeng et al. 2018; Yang et al. 2022).

China is the third largest country on the planet and contains a large highland area (about 63% of the total area), which supports very high biodiversity (Tang et al. 2006; Mi et al. 2019). The highlands of central China are an important habitat for many endemic and endangered species due to their special climate and geological conditions (a subtropical monsoon climate and a geology little affected by quaternary glaciations) (Wu et al. 2003). Some relict species, such as *Davidia involucrata*, *Cercidiphyllum japonicum*, *Emmenopterys henryi* and *Metasequoia glyptostroboides* survived in these highlands through the quaternary glaciations (Lin et al. 2024). Jiugong Mountain is located in Tongshan, a county of Xianning City in China's Hubei Province. Due to its special earth history, biodiversity and landscape, it is listed in the inventory of Chinese National Scenic Areas (approved by the Ministry of Construction of the People's Republic of China) and as part of the National Natural Reserve (approved by the China National Forestry Administration), the National Geopark (approved by the National Forestry and Grassland Administration) and the National 4A level Tourist Attractions (approved by the provincial-level administrative departments of culture and tourism) (Jiugong Mountain 2024). However, information about biodiversity in Jiugong Mountain is very limited, hindering effective conservation and management.

This study provides basic information about the status of, threats to and conservation of biodiversity in the Jiugong Mountain National Natural Reserve (JMNNR). We hope that this study provides useful information about and suggestions for the highlands in central China.

Study area

The JMNNR (114°23'35" – 114°43'24" E, 29°19'27" – 29°26'52" E) is situated in the southeast of Hubei Province, China (Figure 1). It stretches from the county of Wuning in Jiangxi Province in the south to the northern edge of the town of Henshitan in the county of Tongshan. In the east, it extends to the Taiping mountain forest station and the western boundary is connected to the county of Chongyang. The total area of the JMNNRis 17,442.92 ha and the forest coverage is about 90.64%. The JMNNR's average elevation is 1,228 m asl, with the peak in Laoyajian at 1,656.7 m. The JMNNR was established in 1981

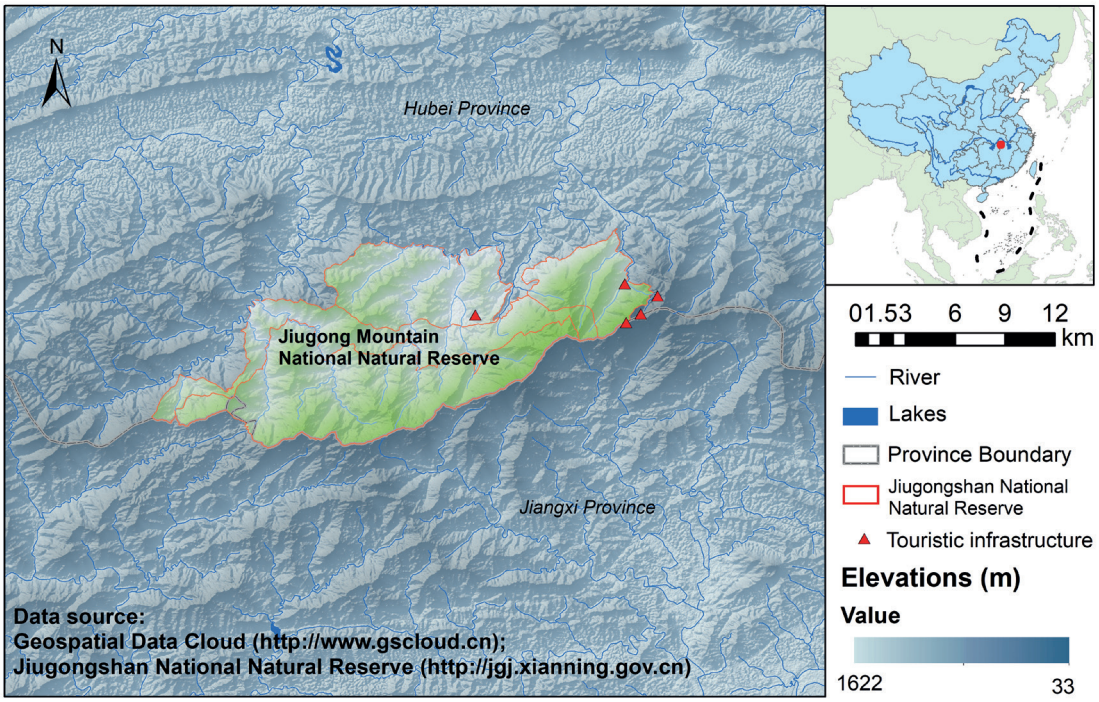


Figure 1– The geographical location and spatial extent of the Jiugongshan Mountain National Nature Reserve

with approval from the Tongshan County People's Government. In 1988, it was upgraded to a provincial-level nature reserve by the Hubei Provincial People's Government. In 2007, it was reclassified as a National Nature Reserve.

Yunzhong Lake is located at the top of Fenghuangling Mountain at an altitude of 1,250 m. Owing to its location on a mountaintop surrounded byclouds, hence its name Yunzhong Lake meaning lake in the clouds. This lake covers an area in excess of 100 acres and is 3.5 m deep on average. Yunzhong Lake is the third largest highland lake in China and its breathtaking beauty attracts many tourists each year.

The climate of the JMNNR is a subtropical monsoon climate. The annual average temperature of the JMNNR increases from 8.8 °C at the southernmost point to 16.7 °C at the northernmost point. The annual average precipitation in the JMNNR is 1,400–2,000 mm (about 73% in the rainy reason, February–June, and only 27% in the dry season), with a highest recorded precipitation of 2,199.8 mm in 1973.

Biodiversity

Building on an investigation of non-native species in China from 2003 to 2024 and the work of the undergraduate research training program of Hubei Normal University from 2021 to 2024, we conducted a series of field investigations about biodiversity in the JMNNR. For the detailed investigation methods, see Wang et al. 2021 and Wang et al. 2024. Based on our investigation and a comprehensive literature review, there are 1983 vascular plant species belonging to 209 families and 857 genera, which account for about 7.1%, 59.2% and 27.0% of the total number of plant species, families and genera of China, respectively. There are 37 endangered plant species distributed in the JMNNR (Table 1) with 24 National Key Protected Plants (two Class I species and 22 Class II species), 15 National Precious Tree Species (three Class I species and 12 Class II species) and 25 National Rare and Endangered Plants (10 Class II species and 15 Class III species). There are some endangered species (such as *Asarum campaniforum* and *Primula hubeiensis*) that have only survived in the JMNNR (Wang et al. 2004; Li et al. 2017).

For National Key Protected Plants (National Forestry and Grassland Administration, Ministry of Agriculture and Rural Affairs of the People's Republic of China 2021a), both class I and class II plants have important ecosystem functions, but there are few individuals and the distribution is narrow. However, class II plants are less threatened than class I.

National precious tree plants are species that are scarce in quantity and have high economic value (Zhang 1993). Class I species are prohibited from being cut down, while class II species are strictly controlled. Class I species of national rare and endangered plants are unique to China and have extremely significant scientific, economic and cultural value. They are either endangered or rare species (State Environmental Protection Agency of the People's Republic of China and the Institute of Botany of the Chinese Academy of Sciences 1987). Class II species are declining species of significant scientific and economic value. Class III plants are rare species with relatively lower economic value than class II.

There is a very high amount of fauna biodiversity in the JMNNR, including 48 mammals belonging to



Figure 2 – Some of the protected animals from the Jiugong Mountain National Natural Reserve. © Kai Zhao

seven orders, 20 families and 33 genera; 146 birds belonging to 15 orders, 38 families and 105 genera; 39 reptiles belonging to two orders, eight families and 26 genera; 27 amphibians belonging to one order, six families and eight genera. Of these, 22 animal species have been included in the List of Endangered Animals of China (five Class I species and 18 Class II species) (Figure 2). All the endangered animal species are shown in Table 2.

Class I protected animals are rare species with a small population, which are endangered or nearly extinct in the wild. Class II protected animals are those that are more numerous than Class I animals (National Forestry and Grassland Administration, Ministry of Agriculture and Rural Affairs of the People's Republic of China 2021b).

Threats to the Jiugong Mountain National Natural Reserve

Human disturbance

Human disturbance is an important threat to biodiversity and ecosystems in hilly regions (Yang et al. 2022). The number of local residents increased from 2,846 in 2000 to 42,992 in 2019 (NBS 2020). For basic survival, local residents have to reclaim more land and have planted maize, tomato and some other vegetables. Due to its beauty and long history (as a Taoist holy place for nearly 800 years), almost half a million tourists visit the JMNNR each year. As a result, massive infrastructure, such as roads, housing, water and power supply facilities, has been built over the past twenty years. Now, national and provincial roads cover the county of Tongshan, connecting every village and town. For example, the newly constructed Yunzhong Lake parking area, which is under the management of the JMNNR Administration, Xianning, Hubei, occupies 12,800 m^2 at the center of the JMNNR (Jiugong Mountain 2024). Roads, pipes and some human dwellings have fragmented the habitat, significantly influencing the migration and gene exchange of many animals and eventually causing the population decline of many native animals (Eigenbrod et al. 2008; Piano et al. 2020).

Invasion of non-native species

Biological invasion is a serious threat to global biodiversity, ecosystem function and environmental health (Sala et al. 2000; Simberloff et al. 2013). China today is one of the countries seriously threatened by the invasion of non-native species (Xu et al. 2012; Xiong et al. 2015; Wang et al. 2016). Indeed, the middle reaches area of the Yangtze River, where the JMNNR is located, is a hotspot for invasion of non-native species (Xiong et al. 2018, 2023a). Comparing our results with field investigation by the Wuhan Botanical Garden and the China University of Geosciences, we recorded invasion by some non-native species in the JMNNR, including *Sesbania cannabina*, *Alternanthera philoxeroides*, *Erigeron annuus*, *Gambusia affinis*, *Oreochromis niloticus*, *Procambarus clarkii*, *Pomacea canaliculate* and *Trachemys scripta elegans*. In a previous study, we observed that these non-native species have caused significantly negative ecological impacts in surrounding regions (Cheng et al. 2018; Xiong et al. 2019, 2023a). These non-native species caused a sharp decline of native biodiversity and changed ecosystem structures and functions.

Small-size hydropower stations

There are many streams and mountain springs in the JMNNR. In order to provide electricity for rural

Table 1 – The list of endangered plant species in the Jiugongshan Mountain National Nature Reserve.

No	Scientific name	National Key Protected Plants	National precious tree species	National rare and endangered plants
1	*Taxus chinensis* var. *mairei*	I	I	
2	*Bretschneidera sinensis*	I	I	II
3	*Cibotium barometz*	II		
4	*Pseudolarix amabilis*	II	II	II
5	*Cephalotaxus oliveri*	II	II	II
6	*Tarreya fargesii*	II		
7	*Tarreya grandis*	II		
8	*Liriodendron chinense*	II	II	II
9	*Magnolia officinalis*	II	II	III
10	*Magnolia officinalis* spp. *biloba*	II		III
11	*Tetracentron sinense*	II	II	II
12	*Cercidiphyllum japonicum* var. *sinense*	II	II	II
13	*Cinnamomum camphora*	II		
14	*Cinnamomum japonicum*	II		III
15	*Phoebe zhennana*	II	II	III
16	*Ormosia henryi*	II	II	
17	*Glycine soja*	II		III
18	*Fagophrum dibotrys*	II		
19	*Zelkova schneideriana*	II	II	
20	*Toona ciliata*	II		III
21	*Toona ciliata* var. *pubescens*	II		
22	*Camptotheca acuminata*	II		
23	*Emmenopterys henryi*	II	I	II
24	*Sinojackia xylocarpa*	II		II
25	*Tilia tuan*		II	
26	*Eucommia ulmoides*		II	II
27	*Kalopanax septemlobus*		II	
28	*Changnienia amoena*			II
29	*Magnolia cylindrica*			III
30	*Coptis chinensis*			III
31	*Coptis chinensis* var. *brevisepala*			III
32	*Stewartia sinensis*			III
33	*Pieroceltis tatarinowii*			III
34	*Tapiscia sinensis*			III
35	*Pterostyrax psilophylla*			III
36	*Dysosma versipellis*			III
37	*Gastrodia elata*			III

residents, some small-size hydropower stations were built in the JMNNR (Tongshan County Government 2024). In order better to protect local biodiversity and aquatic habitats in the Yangtze River Basin, the Chinese central government issued *Opinions on carrying out the cleanup and rectification of small-size hydropower in the Yangtze River Economic Zone* and asked for the shutdown of all small-size hydropower stations in the core areas and buffer areas of Natural Reserves by December 2020 (Chinese Central Government 2018). However, five small-size hydropower stations remained in operation during 2021 and were only dismantled under the supervision of the central inspectors of environmental protection in 2022 (Network of the Development of the Yangtze River Economic Belt website 2021; Tongshan County Government 2022). A third central government ecological and environmental protection supervision group inspired further local government rectifications and reforms. Natural populations of local fish, amphibians, reptiles and other biological groups had decreased sharply due to changes in the hydrobiological situation (Xiong & Jian 2009; Lyu et al. 2022).

Protective suggestions

Biological monitoring is an important preliminary measure for biodiversity conservation (Anderson 2018; Kühl et al. 2020). As a geographical and geological shelter, Jiugong Mountain provides suitable habitats for many endangered flora and fauna. Researchers have reported many newly discovered and described species, such as plants (Xie and Mao 2010; Lu et al. 2024) and insects (Zheng & Zhong 2005) in the JMNNR. This shows that there are rich flora and fauna in the JMNNR. Due to the complex geological conditions in many remote regions of the JMNNR, many researchers find it very hard to reach. Some new technology and equipment, such as remote sensing, UAVs

Table 2 – The list of endangered animal species in the Jiugongshan Mountain National Nature Reserve.

No.	Species	Protection class	Biological group
1	*Aquila chrysaetos*	I	Bird
2	*Syrmaticus ellioti*	I	Bird
3	*Neofelis nebulosa*	I	Mammal
4	*Panthera Genus*	I	Mammal
5	*Panthera tigris* ssp. *amoyensis*	I	Mammal
6	*Hoplobatrachus chinensis*	II	Amphibian
7	*Bungarus multicinctus*	II	Reptile
8	*Manis pentadactyla*	II	Mammal
9	*Cuon alpinus*	II	Mammal
10	*Lutra lutra*	II	Mammal
11	*Martes flavigula*	II	Mammal
12	*Viverricula indica*	II	Mammal
13	*Hydropotes inermis*	II	Mammal
14	*Capricornis sumatraensis*	II	Mammal
15	*Platalea leucorodia*	II	Bird
16	*Aix galericulata*	II	Bird
17	*Accipiter nisus*	II	Bird
18	*Falco tinnunculus*	II	Bird
19	*Pucrasia macrolopha*	II	Bird
20	*Coturnicops exquisitus*	II	Bird
21	*Otus sunia*	II	Bird
22	*Bubo bubo*	II	Bird

(Unmanned Aerial Vehicles) and automatic cameras should more widely be applied for the purposes of biodiversity monitoring in this JMNNR (Petrou et al. 2015; Schöttker et al. 2023). However, more specialist training is urgently required, as are more funds, equipment and professional staff.

In particular, there is an urgent need for more funds and professional staff to protect the remaining small populations of some endangered species, such as *Toona ciliata*, *Changnienia amoena*, *Aquila chrysaetos* and *Falco tinnunculus*. Human disturbance has led to the sharp decline and fragmentation of habitats suitable for these endangered species. The numbers of certain endangered species, such as *Neofelis nebulosa*, *Panthera tigris* ssp. *Amoyensis* and *Hydropotes inermis*, have decreased to less than 20 and so they face extinction in the JMNNR. Thus, we call on local government to provide more funds and researchers for the investigation and conservation of these endangered species. Meanwhile, researchers should put more effort into biodiversity conservation and education in order to lessen the damage done by local residents.

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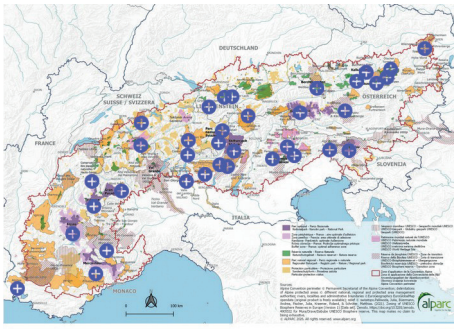
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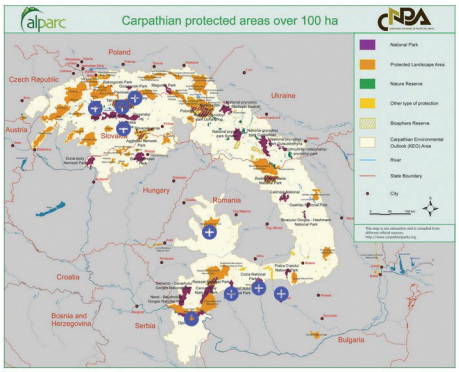
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