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GIS and Remote Sensing-Based Distribution Mapping of Ethnomedicinal Plants in the Tanawal Region of Pakistan

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Abstract
Behold Tanawal's ethnomedicinal flora, located within the biodiversity hotspot of Lesser Himalaya in Pakistan, which sustains the indigenous health systems but is under constant threat from anthropogenic and climatic pressures. A protocol is constructed to map than social and ecological aspects of important ethnomedicinal flora based on the Synthesis of ethnobotanical literature, remote sensing technologies and probabilistic species distributions modeling in Tanawal is explored. This region stretch over four districts covering an elevation range of 500–2,700 m above sea level, illustrating 66–221 high-use medicinal species across 43–105 botanical families, with herbaceous taxa most abundant (62%). Quantitative ethnobotanical metrics show high cultural reliance on Acacia modesta (RFC = 81), Dioscorea deltoidea (UV = 3.6), Withania coagulans (UV = 3.3), and it is also found that harvesting preferentially the underground organs threatens population persistence. Sentin-2 and Landsat-8 multispectral imagery, especially when coupled with spectral vegetation indices (NDVI, EVI, SAVI) and elevation derivatives from DEMs, offers powerful environmental predictors for MaxEnt niche modeling. MaxEnt by using presence-only records obtained predictive accuracy (AUC=0.87--0.969) recognizing temperature and precipitation variables as the preeminent distribution factors. Climate scenarios in 2050 and 2070 under SSP2-4.5 suggest that the high-altitude species' habitat range will contract 11–41% of the area, with emerging invasive species like Parthenium hysterophorus growing up higher altitudes. The synthesis recommends the creation of Medicinal Plant Conservation Areas, with prioritization of strict endemics (Primula hazarica, Berberis parkeriana), high-use taxa to be shifted to community-based cultivation; and combining traditional knowledge with geospatial monitoring to provide sustainable management.

Keywords: Ethnomedicinal plants; GIS; Remote sensing; MaxEnt; Species distribution modeling; Habitat suitability; Climate change vulnerability; Conservation prioritization; Tanawal; Himalaya

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1. Introduction

The Himalayan mountain system is known around the world as a hub of plant diversity. It holds thousands of plant species. Many of these species are found in the Himalayas and have healing properties. In Pakistan the native plant life includes than 6,000 vascular species. About 600 of these species are harvested for medicinal use (Wambulwa et al. 2021). The Lesser Himalayan area of Khyber Pakhtunkhwa province the Tanawal region is a meeting point of ecological and plant geography. Here temperate Himalayan plant elements mix with sub-tropical foothill ecosystems. Local people in this region depend on medicinal plants for basic health care. They keep knowledge about these plants in families for many generations (Rawal et al. 2013). With this strong plant heritage wild medicinal plants are under increasing human pressure. Unregulated harvesting, overgrazing, deforestation and climate-driven habitat breaks threaten them (Tiwari & Rani 2025). Traditional ethnobotanical surveys give qualitative and numeric data about how local people use plants. Still field records by themselves cannot map boundaries, model habitat preferences or predict habitat changes from global warming (Salaria et al., 2025). To fill this gap modern ecological studies, use Geographic Information Systems (GIS) Remote Sensing (RS) and probabilistic Species Distribution Models (SDMs) like Maximum Entropy (MaxEnt). Earth observation satellites such as Sentinel-2 and Landsat-8 allow monitoring of plant canopy changes classification of land cover by light spectra and extraction of biophysical spectral indices (Yang et al. 2025). At the time MaxEnt niche modeling uses field location data together with fine-scale climate, topography and soil variables to measure how suitable habitats are across rugged landscapes (Sharma et al. 2023). This review combines records, remote sensing tools, biophysical spectral indices and probabilistic niche modeling. It sets up a framework for mapping plant distribution evaluating habitats and prioritizing conservation of plant species, in the Tanawal region of Pakistan (Tefera et al., 2024).

2. Physical and Ecological Characteristics of the Tanawal Region

The Tanawal area includes a mountain valley that's part of the Lesser Himalayan area in Khyber Pakhtunkhwa, Pakistan. In terms of geography Tanawal is in four districts: Abbottabad, Haripur, Mansehra and Tor-Ghar (Farooq et al. 2019). The area is between latitudes 34^∘ 21'30"" N" to 34^∘ 48'53"" N". Longitudes 72^∘ 50'34"" E" to 73^∘ 10'30"" E". The total land area in Upper Tanawal is 528 square kilometers. The land has two parts: Upper Tanawal, which has rough mountain areas that go up to 2,700 meters above sea level and Lower Tanawal which has hills, flat areas and lower valleys that go down to about 500 meters above sea level. The average height of the Tanawal area is about 1,374 meters above sea level (Farooq et al. 2019).

Water flows through the region with streams that are always running like the Siran and Ichha rivers and many smaller streams that only run in seasons. The western part of Tanawal ends at the Indus River, which's part of the Tarbela Reservoir area (Bibi et al., 2019). The weather changes from dry and warm at places to wet and cooler at higher places. The area has two times when it rains: winter rain from January to February and strong summer rain from June to August (Farooq et al., 2018). The amount of rain each year is between 600 mm and 1,532 mm depending on the height and direction of the slope. The temperature changes a lot with the height. In the valleys summer can be as hot as 32°C to 41.5°C. In the mountain areas the winter can get cold enough to freeze and there is snow every season (SHAH, 2022).

The plants in Tanawal are part of the Japanese plant area. The kinds of plants change with height. How much water is around. Lower places have forests of green trees and small bushes. The main trees are Acacia modesta, Olea ferruginea and Dodonaea viscosa (Zada, 2015). Mid and high areas have forests of pine trees, which change into mixed forests of broad leaves and other trees, like Quercus, Aesculus indica and Abies pindrow at the top (Bibi & Jamal 2021).

Table 1. Geographic, Climatic, and Ecological Parameters of the Tanawal Region, Pakistan.

Parameter	Operational / Analytical Values	Environmental Significance
Geographic Coordinates	34°21'30'' N–34°48'53'' N, 72°50'34'' E–73°10'30'' E	Delineates the Lesser Himalayan transition zone in KP, Pakistan.
Administrative Coverage	Districts Mansehra, Abbottabad, Haripur, Tor-Ghar	Multi-district spatial extent requiring integrated regional management.
Elevation Range	500 m to 2,700 m asl (Mean: 1,374 m)	Creates microclimatic variability driving steep floristic turnover.
Climatic Zone	Sub-tropical semi-arid to moist temperate	Supports diverse plant functional types across altitudinal strata.

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Parameter	Operational / Analytical Values	Environmental Significance
Annual Rainfall	600 mm to 1,532 mm	Governs soil moisture availability and seasonal vegetation greenness.
Hydrological Network	Siran River, Ichha River, Indus River catchment	Provides riparian microhabitats critical for moisture-dependent herbs.
Phytogeographic Region	Sino-Japanese Region	High degree of floral diversity, including Himalayan endemics.

3. Ethnobotanical Diversity and Quantitative Flora Analysis

Floristic evaluations in the Tanawal area document vascular plant diversity with Upper Tanawal hosting over 308 tracheophyte species. Comprehensive ethnobotanical investigations specifically addressing medicinal plants report between 66 and 221 high-use species spanning 43 to 105 families (Begossi, 1996). Taxonomic distribution analysis reveals that herbaceous species dominate the flora representing approximately 62 % of documented taxa followed by trees at 22 % and shrubs at 16 %. The Mesophanerophyte life-form dominates the tree spectrum at 64 % indicating mesic environmental conditions across mid-altitude forest stands (Sulaiman et al., 2020).

The predominant plant families contributing to the flora of Tanawal include Asteraceae, Solanaceae, Lamiaceae, Fabaceae, Rosaceae, Ranunculaceae, Poaceae and Brassicaceae. Asteraceae and Solanaceae routinely record the highest species richness in surveys (Vijayakumar et al. 2015). Among taxa high usage frequency and ecological dominance are reported for Berberis lycium, Justicia adhatoda, Mentha longifolia, Geranium wallichianum, Isodon rugosus, Silybum marianum, Dioscorea deltoidea, Acacia modesta, Acorus calamus and Withania coagulans (Weckerle et al., 2011).

Quantitative ethnobotanical metrics such as the Relative Frequency of Citation (RFC) Use Value (UV) and Fidelity Level (FL) provide measures of cultural reliance and species importance. High RFC values reaching up to 81 have been documented for Acacia modesta, Citrullus vulgaris, Tamarindus indica and Momordica charantia signifying community consensus regarding their utility (Kefifa et al. 2020). The Use Value index, which reflects the degree of utilization per species reaches maximum values in specialized taxa such as Dioscorea deltoidea ("UV" = 3.6) Momordica charantia ("UV" = 3.5) Withania coagulans ("UV" = 3.3) Silybum marianum ("UV" = 3.2) and Pyrus pashia ("UV" = 3.2). Additionally high Fidelity Level percentages ("FL" = 95.2 %) reflect therapeutic targeting for designated ailments (Begum et al. 2024).

Analysis of plant part utilization reveals that leaves are the frequently harvested anatomical component (21 % to 43.28 %) followed by fruits and seeds (15 % to 21 %) whole plants (14 % to 18 %) barks (9 % to 12 %) roots and rhizomes (4 % to 9 %) and flowers (7 % to 16 %). Although leaves represent a resource the targeted harvesting of underground organs such as roots, rhizomes and tubers poses a direct threat to population persistence (Al-Robai et al., 2022). High local demand for the roots of Dioscorea deltoidea, Berberis lycium and rare endemics such, as Berberis parkeriana, Primula hazarica and Thalictrum secundum var. hazaricum accelerates population decline. High quantitative ethnobotanical values directly correlate with harvesting pressure highlighting the need for mapping to identify critical natural populations (Shah et al. 2023).

Table 2. Key Ethnomedicinal Plant Taxa of Tanawal, Therapeutic Uses, and Quantitative Indices.

Species Name	Family	Local Name	Harvested Part	Major Therapeutic Application	RFC	UV	FL (%)
Acacia modesta Wall.	Fabaceae	Phulai / Palosa	Bark, Gum, Leaves	Stimulant, tonic, internal wound healing, toothcare	81	2.8	95.2
Berberis lycium Royle	Berberidaceae	Sumbal	Roots, Bark, Leaves	Jaundice, typhoid, diabetes, wound healing, bone fractures	71	3.1	88.5
Dioscorea deltoidea Wall. ex Griseb.	Dioscoreaceae	Kanis	Rhizome, Roots	Rheumatic pain, abdominal disorders, contraceptive agent	64	3.6	91.0
Justicia adhatoda L.	Acanthaceae	Bhaikarr	Leaves, Roots, Flowers	Respiratory tract infections, asthma, cough, stimulant	31	1.8	65.4

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Species Name	Family	Local Name	Harvested Part	Major Therapeutic Application	RFC	UV	FL (%)
Silybum marianum (L.) Gaertn.	Asteraceae	Oontkattara	Whole plant, Seeds	Hepatitis, liver cirrhosis, jaundice, digestive disorders	52	3.2	82.1
Withania coagulans Dunal	Solanaceae	Panir dodi	Fruits, Seeds	Diabetes, gastric pain, blood purification, dyspepsia	48	3.3	86.7
Geranium wallichianum D. Don	Geraniaceae	Ratanjot	Roots, Whole plant	Joint pain, backache, kidney disorders, tonic	58	2.9	79.3
Acorus calamus L.	Acoraceae	Baabchee	Rhizome	Children's teething, rheumatism, stomach disorders	42	2.1	72.0
Isodon rugosus (Wall. ex Benth.) Codd	Lamiaceae	Sperkai	Leaves, Seeds	Toothache, fever, abdominal pain, diarrhea	60	2.4	81.5
Mentha longifolia (L.) L.	Lamiaceae	Vemba / Pudina	Leaves, Whole plant	Diarrhea, dysentery, vomiting, digestive carminative	69	2.7	84.0

4. Remote Sensing and Geospatial Analytical Frameworks

High-resolution, multispectral satellite images from Sentinel-2 (MultiSpectral Instrument, MSI) and Landsat-8 (Operational Land Imager, OLI) form the foundation of the remote sensing framework applied in this study to map the distribution of ethnomedicinal plants (Tragia, 2025). The 10-meter spatial resolution in the visible and Near-Infrared (NIR) bands of Sentinel-2, alongside its dedicated Red-Edge spectral bands (Bands 5, 6, 7, and 8A), which react strongly to small changes in leaf chlorophyll, leaf area index (LAI), and canopy characteristics, would make it particularly suitable for complex mountainous landscapes like those found in the Tanawal area (Mumtaz et al., 2025). Spectral vegetation indices derived from multispectral bands serve as proxy environmental variables that capture plant phenology, canopy moisture, and photosynthetic activity across altitudinal gradients (Crabtree et al., 2009). The Normalized Difference Vegetation Index (NDVI) measures overall greenness and vegetation vigour:

$$\mathrm{NDVI} = \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{Red}}}{\rho_{\mathrm{NIR}} + \rho_{\mathrm{Red}}}$$

In areas with dense forest cover, such as *Pinus roxburghii* stands in Upper Tanawal, NDVI exhibits spectral saturation (Goodchild & Quattrochi, 2023). To compensate, the Enhanced Vegetation Index (EVI) incorporates blue band reflectance to adjust for atmospheric background and canopy structural variations:

$$\mathrm{EVI} = G \cdot \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{Red}}}{\rho_{\mathrm{NIR}} + C_1 \cdot \rho_{\mathrm{Red}} - C_2 \cdot \rho_{\mathrm{Blue}} + L}$$

where $G = 2.5$, $C_1 = 6.0$, $C_2 = 7.5$, and $L = 1.0$.

On rocky, sparsely vegetated slopes common in degraded lower valley regions, soil background interference distorts spectral reflectance values. The Soil-Adjusted Vegetation Index (SAVI) addresses this by introducing a soil-brightness correction factor (L_s):

$$\mathrm{SAVI} = \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{Red}}}{\rho_{\mathrm{NIR}} + \rho_{\mathrm{Red}} + L_s} \cdot (1 + L_s)$$

where $L_s = 0.5$ is standard for intermediate vegetation density (Calvert et al., 2013).

Digital Elevation Models (DEMs) such as the 30-meter Shuttle Radar Topography Mission (SRTM) or ALOS PALSAR datasets can provide important physiographic and hydrological variables in addition to satellite-derived vegetation indices (Metternicht et al., 2005). Topographic factors such as slope angle, aspect (sunlight or shade), hillshade, and the Topographic Wetness Index (TWI) directly affect microclimate and soil moisture retention, as well as plant distribution patterns on a local scale. By incorporating multispectral vegetation indices and topographic metrics in a GIS environment, a spatial ecological niche database can be constructed (Giachetta, 2015).

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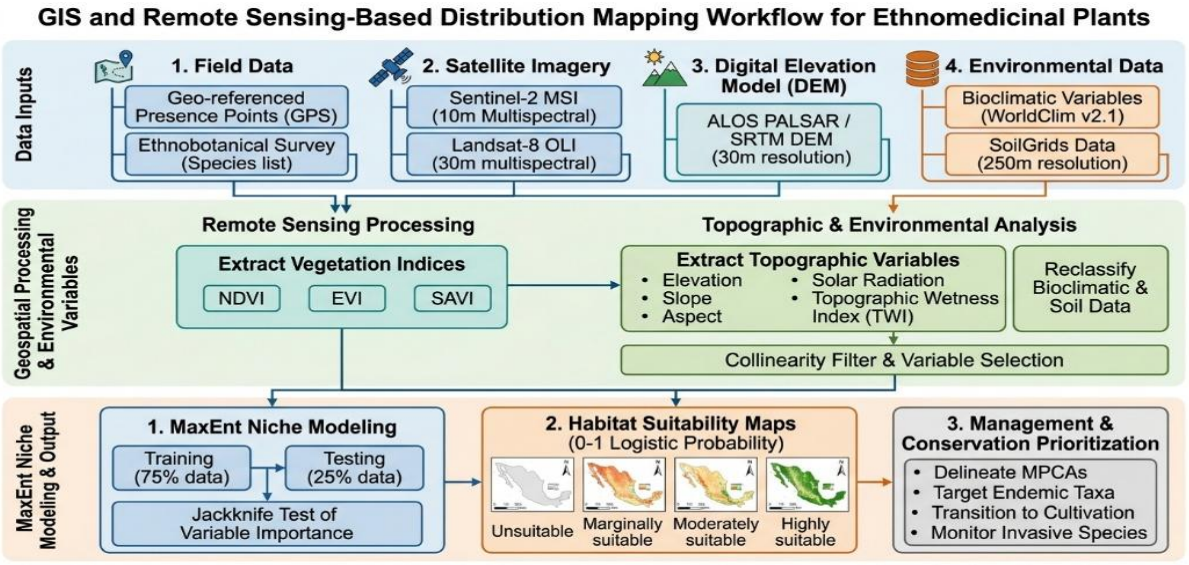

Figure 1. Schematic Workflow of GIS, Remote Sensing, and MaxEnt Integration for Ethnomedicinal Plant Distribution Mapping in the Tanawal Region.

Table 3. Remote Sensing Platforms, Spectral Indices, and Spatial Inputs for Species Distribution Modeling.

Parameter / Data Source	Spatial / Spectral Resolution	Derived Variables / Indices	Ecological Analytical Function
Sentinel-2 MSI	10 m–20 m (13 Spectral Bands)	NDVI, EVI, SAVI, Red-Edge Position (REP), NDRE	Discriminates canopy greenness, chlorophyll content, and fine-scale habitat structure.
Landsat-8 OLI	30 m (Multispectral), 15 m (Panchromatic)	Multi-temporal NDVI, Land Surface Temperature (LST)	Tracks long-term phenological changes and surface thermal dynamics.
SRTM / ALOS DEM	30 m Spatial Resolution	Elevation, Slope, Aspect, Solar Radiation, TWI	Models terrain-driven microclimates, hydrologic accumulation, and sun-exposure gradients.
WorldClim v2.1	30 arc-seconds (≈1 km^2)	19 Bioclimatic variables (Bio-1 to Bio-19)	Quantifies macro-climatic envelopes including temperature and precipitation regimes.
SoilGrids / HWSD	250 m–1 km Spatial Resolution	Soil pH, Organic Carbon, Texture, Moisture Content	Evaluates edaphic suitability and substrate constraints on root establishment.

5. Maximum Entropy (MaxEnt) Niche Modeling and Predictive Analytics

Maximum Entropy MaxEnt niche modeling is a known machine learning method used to predict where plants can grow. MaxEnt works well for studies in places like the Himalayas because it uses data that shows where a species is found. It does not need data that shows where a species is not found which is hard to get in mountain areas (Moreno et al., 2011). The math behind MaxEnt finds the likely way a species spreads based on the environment where it is known to live (Yost et al., 2008).

The MaxEnt process takes data from the field like GPS points where a species is found and combines it with maps showing things like temperature, rainfall and other climate data. It also uses satellite data, maps of the land and information about what kind of land cover's there (Slater, H., & Michael 2012). To make sure the model is not too simple or too complex the data is carefully checked. Any data that is too similar is removed (Cobos et al. 2019).

How well the model works is checked using a number called AUC. AUC goes from 0 to 1. If it is below 0.5 the model is not better than random. If it is between 0.7 and 0.8 the model is okay. If it is between 0.8 and 0.9 the model is good. If it is above 0.9 the model is very accurate (Warren & Seifert 2011). In studies in the Himalayas MaxEnt has AUC values that are high like between 0.87 and 0.969. This shows that MaxEnt is reliable, for finding where plants can grow (Fitzgibbon et al., 2022).

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To find out what factors most influence where a species lives MaxEnt uses a test called Jackknife. This test looks at how each factor affects the model when it is used alone or left out (Urbani et al., 2017). MaxEnt gives a number between 0.0 and 1.0 to show how likely a place is to have a species. This number is then split into four levels: not good, a little good somewhat good and very good. This helps people who plan conservation areas decide where to focus their work (Papeş et al. 2016).

6. Environmental Drivers and Climate Change Vulnerability

I notice that MaxEnt niche modeling studies across Khyber Pakhtunkhwa and the broader Western Himalayan region reveal that temperature and precipitation variables control species distribution models for plants (Adger, 2006). Among the 19 bioclimatic metrics Isothermality (Bio-3 = [Mean Diurnal Range / Temperature Annual Range] × 100) Annual Precipitation (Bio-12) Precipitation of the Wettest Month (Bio-13) Precipitation of the Wettest Quarter (Bio-16) and Precipitation of the Coldest Quarter (Bio-19) consistently give the percentage contributions in Jackknife evaluations (Fazey et al., 2010). Isothermality and seasonal precipitation regimes put physiological limits on high-value ethnomedicinal taxa. For example niche models for taxa such as Nepeta griffithii, Abies. Juniperus excelsa show that wettest-quarter precipitation and diurnal thermal fluctuations set survival thresholds, seed germination timing and secondary metabolite synthesis (Duvat et al. 2017). In Tanawal steep topographic gradients create microclimates where altitudinal aspect changes solar radiation, soil moisture retention and surface temperature creating distinct micro-refugia for sensitive species such as Dioscorea deltoidea and Geranium wallichianum (Räsänen et al., 2016). Projections under Coupled Model Intercomparison Project Phase 6 (CMIP6) Shared Socioeconomic Pathways (SSPs) such as the emissions scenario (SSP2-4.5) show marked shifts in potential habitat distribution across the Himalayan range by 2050 and 2070 (Kling et al. 2020). Climate projections indicate that high-altitude and sub-alpine ethnomedicinal species face a habitat contraction of 11 % to 41 %. Spatial niche modeling shows an upward altitudinal shift and a northeastward migration vector toward higher elevations as species follow their shifting climatic envelopes (9v et al., 2009). In the Tanawal region warming trends and changing monsoon patterns threaten low-. Mid-elevation medicinal flora. Species adapted to sub-tropical Chir pine and broad-leaved evergreen forest zones face aridity, higher fire frequency and competition from invasive alien weeds (Thornton et al. 2014). Notably aggressive invasive species such as Parthenium hysterophorus spread along roadsides and degraded forest edges in Lower Tanawal pushing out ethnomedicinal herbs like Artemisia scoparia and Bidens pilosa. Furthermore narrow endemic taxa with geographic ranges, such, as Primula hazarica, Berberis parkeriana and Thalictrum secundum var. Hazaricum, have limited ability to move, putting them at risk of local extinction as warming speeds up (Benson, 2020).

7. Conservation Prioritization and Sustainable Management Strategies

Combining ethnobotanical metrics with remote sensing data and MaxEnt model results creates a clear structure for spatial conservation prioritization across the Tanawal landscape. By overlaying GIS layers that show where habitat suitability is projected to be high with data on human disturbance, road networks and degraded land cover conservation managers can locate critical threat hotspots and focus intervention zones (Carwardine et al. 2019).

High-suitability habitat clusters identified by MaxEnt models inside intact mid-to-high elevation forest stands in Upper Tanawal give a scientific basis for setting up protected Medicinal Plant Conservation Areas (MPCAs). Giving protected status to these habitats can keep fragile populations of *Dioscorea deltoidea* *Geranium wallichianum* and *Berberis lycium* from land conversion, agricultural expansion and unregulated commercial harvesting (Carwardine et al. 2012).

Narrow endemic taxa that live in niche envelopes and have high therapeutic value, such as *Primula hazarica* *Berberis parkeriana* and *Salix denticulata* subsp. *Hazarica* need in-situ monitoring and focused conservation. Sensing-derived micro-habitat mapping lets researchers find micro-refugia across rugged terrain guiding targeted field surveys and seed collection for ex-situ germplasm banking and botanical garden propagation (Wu et al., 2014).

Ethnomedicinal taxa that show Use Values and high Relative Frequencies of Citation like *Acacia modesta* *Withania coagulans* and *Silybum marianum* should shift from wild harvesting to community-based agroforestry and nursery cultivation (Moilanen et al., 2011). Setting up cultivation zones in suitable land classes identified by spatial models can ease harvesting pressure on wild forest populations while giving sustainable economic opportunities to local landholders (Ferrari et al. 2019).

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Multi-temporal remote sensing monitoring that uses indices such as NDVI and SAVI allows continuous tracking of invasive alien species across Tanawal, especially the spread of *Parthenium hysterophorus* along disturbed corridors. GIS-guided ecological restoration protocols should first aim to bring native broad-leaf trees and medicinal shrubs in invaded areas to rebuild ecosystem resilience (Utami et al., 2020).

Combining traditional knowledge with spatial planning ensures that indigenous communities take part directly in resource governance. Training harvesters in non-destructive collection methods, such as rotational harvesting and keeping root crowns is essential for keeping populations alive (Qu & Lu 2018). Co-management frameworks that mix stewardship with geospatial monitoring build a solid base, for long-term biodiversity preservation (Rana et al. 2020).

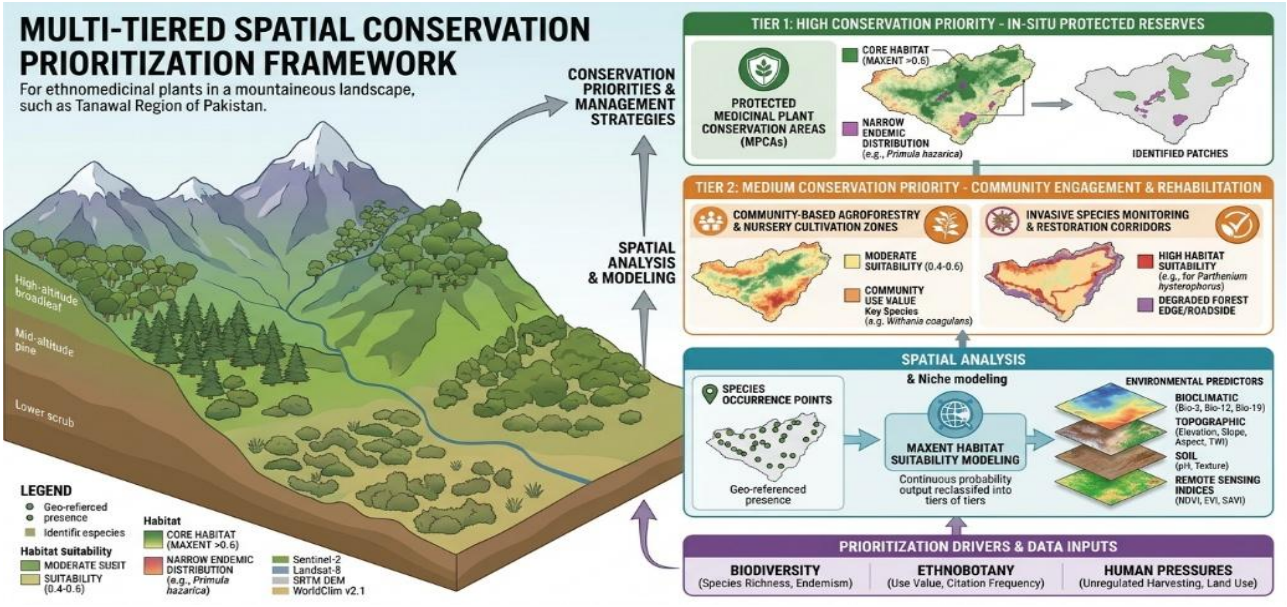

Figure 2. Multi-Tiered Spatial Conservation Prioritization Framework for Ethnomedicinal Flora in the Tanawal Region.

Conclusion

This review shows that combining quantification, remote sensing and MaxEnt niche modeling creates a strong scientific way to map and protect medicinal plant resources in the Tanawal region. The synthesis tells us that Tanawal has a flower life, with up to 221 important medicinal species, mostly in mid-to-high elevation forests where temperature and rainfall decide where species can live. Spectral vegetation indices such as NDVI, EVI and SAVI from Sentinel-2 and Landsat-8 pictures with topographic data from DEMs capture the small climate differences that control the presence of medicinal plants on steep altitude changes. MaxEnt modeling shows reliable predictions with AUC values between 0.87 and 0.969 for finding suitable habitats. This lets us draw core conservation zones and danger spots when we add disturbance layers. Climate change forecasts from CMIP6 scenarios say that high-altitude species may lose 11–41% of their habitat. The species that live at the top may move upward putting endemics that cannot move far at risk. The review points to priority actions: set up Medicinal Plant Conservation Areas in the spots of Upper Tanawal; watch these plants in the wild and store their seeds or cuttings for species like Primula hazarica and Berberis parkeriana; move common species such as Acacia modesta Withania coagulans and Silybum marianum into community agroforestry; and use remote sensing, over time to track the invasive plant Parthenium hysterophorus along disturbed paths. For success we need co-management that mixes local botanical knowledge with map monitoring teaches local harvesters how to collect without harming plants and lets communities become true guardians of Tanawal's medicinal plant heritage. This combined geospatial-ethnobotanical method can be copied for protecting biodiversity in the Himalayan area.

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