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Status of a Critically Endangered Medicinal and Aromatic Herbs *Nardostachys jatamansi* DC. in Alpine Meadows of Nepal

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Abstract

Background: The Himalayan endemic and critically endangered *Nardostachys jatamansi DC* (Jatamansi), a highly prized medicinal and aromatic plant, is of great ecological, cultural, and socioeconomic significance. However, overharvesting, habitat degradation, and climate-induced range shifts are rapidly threatening its wild populations, necessitating robust ecological and management evidence at community forest levels.

Methods: This study conducted a comprehensive ecological assessment across the high-altitude Community Forest User Groups in 5 districts. Data were collected from nested sample plots supported by participatory resource mapping. Growing stock, population density, regeneration status, and annual allowable harvest (AAH) were estimated. Trade trends and traditional uses were assessed through interviews and secondary data review.

Results: The average dry rhizome growing stock ranged from 39.9 to 295 kg ha^{-1}, while mature plant density varied between 195 and 999 individuals ha^{-1} and regeneration density between 139 and 1,066 individuals ha^{-1}. Mugu district exhibited comparatively stronger populations. Despite frequent over extraction beyond sustainable levels, Higher production in terms of growing stock was associated with north-facing slopes, peak productivity occurred in 3,700–3,900 m as it represents a unique and significant productive niche. Ethnobotanical surveys documented 27 traditional uses, particularly for mental health, ritual purification, and cardiovascular ailments.

Conclusion: Findings of this study indicates the urgency of development of the species-specific sustainable harvesting guidelines, community-based monitoring & traceable system.

Novelty: This study integrates ecological inventory, ethnobotany, and harvest estimation at CFUG level, providing rare field-based evidence for sustainable management of *N. jatamansi* in Nepal's alpine ecosystems.

Keywords: Alpine Meadows, Community Forests, Medicinal Plant, Sustainable Harvesting

Introduction

Nepal's Himalayan region is home to an immense diversity of medicinal and aromatic plants (MAPs), several of which function as both substantial sources of livelihoods for mountain communities and ecological indicators. One of the most important species for culture and commerce is Nardostachys jatamansi DC, also referred to as Jatamansi. A perennial herb native to the eastern Himalayas, *N. jatamansi* grows delicately and is cherished for its strong, fragrant rhizomes, which are used extensively in Tibetan, Chinese, Ayurvedic, and Unani medicine (Manandhar, 2002; Sharma, 2000; Chen & Mukherji, 2013;(Bhattacharya & Dhiman, 2020)). This species is found in the Caprifoliaceae (formerly Valerianaceae) family and grows between 3,000 and 5,000 meters above sea level. It is frequently found on damp rocky slopes, alpine meadows, and beneath juniper and rhododendron thickets (Bhat & Malik, 2020; Chauhan et al., 2021; Kaur et al., 2020).

Nardostachys jatamansi plays an important ecological role in stabilizing fragile alpine soil and contributing to habitat diversity. Its rhizomatous growth helps mitigate soil erosion while providing shelter to associated species in high-altitude ecosystems(Bhattacharya & Dhiman, 2020). Culturally and ethnobotanically, it has been a cornerstone of traditional healthcare in Nepal, commonly used to treat neurological, cardiovascular, and digestive ailments. Ethnobotanical surveys from districts such as Jumla, Humla, Bajhang, and Dolpa show that communities use dried rhizomes for treating epilepsy, mental unrest, high blood pressure, and gastrointestinal issues (Kunwar et al., 2006; Pandey et al., 2013); Subedi et al., 2014). The plant is also associated with spiritual purification rites and ritual incense, widely traded as "Spikenard" in international perfumery markets(Khakurel et al., 2024; Pathak & Godela, 2024).

In Ayurveda, Jatamansi is classified as a medhya rasayana, an herb that improves mental acuity and balances the nervous system(Pandey et al., 2013). Its rhizomes yield essential oil rich in sesquiterpenes like nardol, jatamansone, and patchouli alcohol, which exhibit sedative, anti-inflammatory, and neuroprotective properties (Raina & Negi, 2015; Sharma et al., 2016; Panara et al., 2020; Pathak & Godela, 2024). According to Dhiman et al. (2020) refined oil is utilized in herbal remedies, fragrance blends, and high-end cosmetic formulations worldwide. With regard to its fixative properties and earthy-musky undertones, which prolong the olfactory life of blended oils, Jatamansi oil is prized in perfumery (Gurung, 2009). The raw dried rhizomes and their semi-processed form (marc) are exported mostly to China, India, and Europe, and are an essential part of Nepal's green commodity trade(Dhiman et al., 2020a).

Nevertheless, the growing commercial demand, combined with weak regulation and limited regeneration data, has put considerable pressure on wild populations of N. jatamansi. Due to

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its wide range of uses in conventional medicine and extreme overexploitation, alongside a small reproductive phase and low germination rate (10–20%), as reported by Kaur et al. (2020), it is presently on the brink of extinction. Lately, the International Union of Conservation of Nature (IUCN) Red List of threatened species has listed N. *jatamansi* as a critically endangered (CR) medicinal plant (Ved et al., 2014). Due to illegal and over- harvesting, this species is also categorized in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (Nath Maurya et al., 2023) and designated as endangered in Nepal's Conservation Assessment and Management Plan (CAMP, 2001), the species' survival is imperiled by habitat loss and genetic erosion, which reduce genetic diversity, reproductive success, and long-term viability(Aguilar et al., 2019; Pflüger et al., 2019; Pinto et al., 2024). Overharvesting, without adherence to sustainable protocols, has resulted in fragmented populations, low reproductive output, and diminishing viable stock in community forests. A recent study by Rana et al. (2020) applying MaxEnt modeling to habitat prediction revealed that warming temperatures and human land-use patterns could drastically diminish suitable habitats for *N. jatamansi* over the next few decades.

This conservation crisis is exacerbated by the species' intrinsically slow growth rate and limited ecological niche. Although mature rhizome harvesting can take as long as three years from germination, collectors frequently uproot immature plants, further destabilizing population dynamics (ANSAB, 2010). The combination of climate stress, soil disruption from harvesting, and lack of cultivation protocols continues to imperil its survival in the wild. Despite a government ban on exporting raw Jatamansi in 1995 (MFSC, 2014), enforcement remains uneven, and cross-border informal trade persists in districts near India and China.

Even so, *N. jatamansi* continues to play a key role in the financial lives of people in rural areas, notably in Karnali and Sudurpaschim regions. These provinces have high levels of poverty and limited returns from farming. In districts such as Humla, Darchula, Mugu, Bajhang, and Dolpa, families get additional money by gathering MAPs. They commonly use Jatamansi as a means of exchange in local, unofficial markets, or sell it to buyers who are set up at collection spots along the roads. According to Subedi et al. (2017), over 25 tons of Jatamansi are traded annually across the country. However, this number may be much larger due to both underreporting and unregulated harvesting. The government believes that upwards of 200,000 Nepalese individuals depend on income from MAPs (Joshi, 2008).

Research objectives

The core objectives are to accurately measure the existing stock levels, to scrutinize the patterns of regeneration, and to estimate the Annual Allowable Harvest (AAH) for *N. jatamansi*, considering variations based on elevation and aspect. While the specific objectives are:

1. To quantify the growing stock, density, and regeneration status of *N. jatamansi* in selected community forests.
2. To estimate the species-specific annual allowable harvest (AAH) and along the spatial variation across elevation and aspect gradients.
3. To identify threats to habitat and species sustainability and propose conservation actions rooted in community forestry frameworks.

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Review of literature

The Himalayan region serves as a global repository of medicinal and aromatic plants (MAPs), many of which are under significant threat due to anthropogenic and climatic pressures (Khakurel et al., 2024). *Nardostachys jatamansi* DC., a critically endangered, endemic herb, epitomizes this conservation crisis, making it the focus of recent interdisciplinary research aimed at reconciling its ecological fragility with its immense socio-economic value. This review synthesizes the latest scientific literature (within the last five years) to contextualize the research problem by examining three interconnected themes: (1) ecological status and threats, (2) ethnobotanical significance and trade dynamics, and (3) conservation and sustainable management strategies.

Recent ecological assessments confirm the precarious status of *N. jatamansi* in its native habitat. Chauhan et al. (2021) provided a comprehensive review of its biology and conservation, classifying it as critically endangered and highlighting habitat fragmentation and overharvesting as primary drivers of decline. This aligns with global patterns of habitat loss reducing plant progeny quality, as synthesized by Aguilar et al. (2019). Species distribution modeling (SDM) has become a critical tool for predicting climate change impacts. Rana et al. (2020) used MaxEnt modeling to project significant reductions in climatically suitable habitats for high-value MAPs, including *N. jatamansi*, in Nepal under future warming scenarios, identifying a potential upward range shift and habitat contraction. This niche compression under changing thermal regimes is a documented threat to alpine specialists (Sigdel et al., 2020). Furthermore, genetic studies highlight cascading effects; Pflüger et al. (2019) demonstrated that habitat loss leads to non-linear genetic erosion in specialist species, eroding adaptive potential, a risk applicable to fragmented *N. jatamansi* populations. Pinto et al. (2024) further elaborated on the genomic erosion resulting from population fragmentation, underscoring the long-term viability threats beyond immediate population declines.

The cultural and economic embeddedness of *N. jatamansi* continues to be a focal point of ethnobotanical research, which now increasingly documents use trends and market links. Khakurel et al. (2024) conducted a comprehensive risk assessment for valuable Nepalese medicinal plants, identifying *N. jatamansi* as highly vulnerable due to high use values and commercial demand exceeding sustainable supply. Detailed phytochemical and pharmacological reviews, such as that by Pathak and Godela (2024), consolidate evidence for its neuroprotective, sedative, and anti-inflammatory properties, directly explaining its sustained demand in Ayurvedic, Tibetan, and global herbal markets. This demand fuels informal trade networks. Studies on trade governance, though fewer in the last five years, reference persistent issues identified earlier: Olsen and Helles (1997) outlined the "market and margins" dilemma where high value incentivizes overharvesting amidst weak enforcement, a paradox that recent policies have struggled to resolve. The species' listing in CITES Appendix II (as noted by Nath Maurya et al., 2023) is a direct policy response to unsustainable international trade, though implementation challenges remain. Research by Bhattarai et al. (2019) on forest certification

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suggests that mechanisms like FairWild could bridge this governance gap, but uptake in community forestry contexts remains limited.

The search for viable conservation strategies has shifted towards integrating ecological baselines with community-based management. The concept of "dynamic conservation corridors" responsive to climate shifts is gaining traction (Sigdel et al., 2020). For in-situ management, precise ecological baselines are foundational. Studies like that of Kaur et al. (2020) not only reiterated the species' critical status but also detailed its low germination rates and specific habitat requirements, providing the biological justification for regulated harvesting. This aligns with the principles of the IUCN's conservation planning. The role of Community Forest User Groups (CFUGs) as key management entities is central in the Nepalese context. Research by Charmakar et al. (2021) on carbon and biodiversity in certified vs. non-certified community forests demonstrates that structured, incentivized community management can lead to better conservation outcomes. However, a significant research gap persists in developing and testing species-specific, spatially-explicit sustainable harvest protocols (like Annual Allowable Harvest - AAH) for alpine MAPs within CFUG operational plans. Most existing guidelines, including the Government of Nepal's NTFP inventory guidelines (2012), offer generalized frameworks but lack the ecological resolution needed for species as vulnerable as *N. jatamansi*.

Methods

Study Area

This study covers five ecologically diverse districts of western Nepal Jumla, Mugu, Humla, Bajhang, and Darchula spanning an altitudinal gradient from subtropical valleys (~500 m) to alpine and nival zones above 7,000 m. Jumla, located in the mid-western hills, has a subarctic climate with cold winters, mild summers, a mean annual temperature of about 7.2°C, and annual precipitation of approximately 1,256 mm, largely during the monsoon. Mugu, northeast of Jumla, exhibits similar thermal conditions (7.36°C) but receives considerably lower rainfall, concentrated in July–August (DHM, 2020). Humla, Nepal's northernmost district, ranges from 1,500 m to over 7,000 m and is dominated by alpine and subalpine zones, characterized by cold, dry winters and cool summers. Bajhang, in the far-western hills, has a cool summer–dry winter climate at a mean elevation of 2,927 m. Darchula, bordering India and Tibet, is influenced by the Mahankali River system and experiences a humid subtropical climate with monsoon-driven rainfall (Weather & Climate, 2025), Fig 1.

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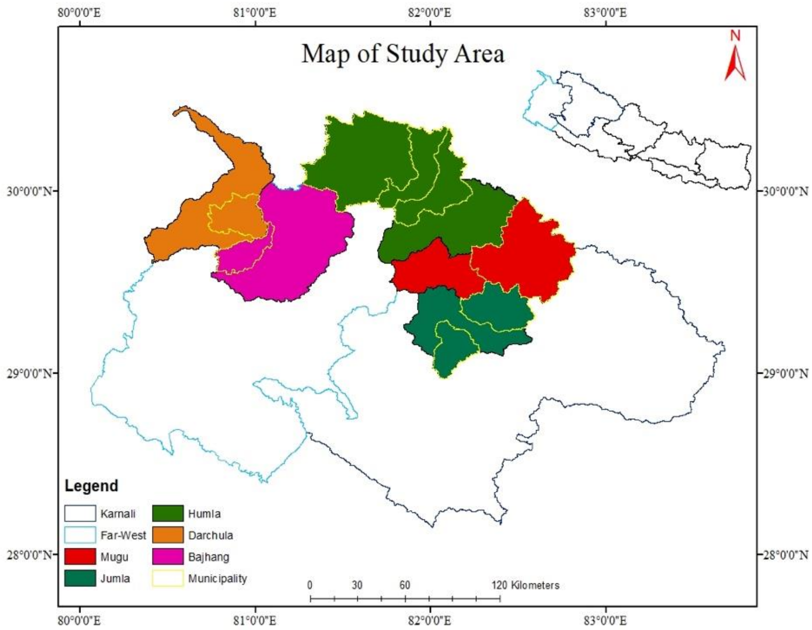

Fig. 1: Location of the study area

Vegetation transitions from temperate broadleaf forests at mid-elevations to subalpine coniferous stands and alpine shrublands at higher altitudes. In the temperate zone (2,000–3,000 m), forests are predominantly made up of species such as *Acer spp., Juglans regia, Aesculus indica, Ulmus wallichiana, and Populus ciliata*, often interspersed with agricultural terraces and community-managed woodlots (Bhatta et al., 2021; Bhattacharjee et al., 2017). These forests are vital for providing critical ecosystem services and serve as habitats for a diverse range of fauna.

The subalpine zone (3,000–4,100 m) is characterized by dense stands of *Abies spectabilis* (silver fir), *Betula utilis* (Himalayan birch), and various species of Rhododendron, forming ecotonal belts that are ecologically sensitive and vulnerable to climatic changes (MoFE, 2018). In the alpine zones (4,100–5,500 m), vegetation is sparse and includes species such as *Juniperus indica, Rhododendron anthopogon*, and alpine meadows rich in herbaceous flora. These regions are particularly significant for high-value non-timber forest products (NTFPs) like *Nardostachys jatamansi, Valeriana jatamansi, Picrorhiza kurroa, and Rheum australe*, which are harvested for both traditional medicine and commercial trade (Kunwar et al., 2013). The study area has 201,958 hectares of forest cover, a critical natural resource of the region (MoFE, 2018). Forest land provides essential ecosystem services and tremendous potential for sustainable business expansion via NTFP and MAP harvesting (Bhatt et al., 2021; MoFE, 2021). (Table 1).

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Table 1: Presents the details of the selected local levels

SN	District	Municipality	Total area (ha)	Total forest area (ha)	Forest Percentage (%)
1	Humla	Simikot Rural Municipality	78,246	9,834	12.6
		Kharpunath Rural Municipality	87,631	16,420	18.7
		Namkha Rural Municipality	240,805	30,705	12.8
2	Mugu	Mugum Karmarong Rural Municipality	209,952	40,968	19.5
3	Jumla	Patarasi Rural Municipality	81,105	27,961	34.5
		Tatopani Rural Municipality	52,341	24,025	45.9
4	Bajhang	Bungal Municipality	44,502	24,985	56.1
5	Darchula	Apihimal Rural Municipality	61,041	27,060	44.3
			855,623	**201,958**	

A total of 29 Community Forest User Groups (CFUGs) across five high-altitude districts- Humla, Mugu, Bajhang, Jumla, and Darchula- were selected based on prior occurrence records, ecological suitability, and community dependence on NTFPs. These CFUGs collectively steward over 10,307 hectares of forest and alpine meadow habitats, ranging between 2,500 m and 4,700 m above sea level, which represent the core altitude of *N. jatamansi* (Chauhan et al., 2021; Dhiman et al., 2020a). The study was conducted between April 2022 and October 2023, encompassing both the pre-monsoon and post-harvest seasons to capture phenological variations and harvesting practices.

Data Analysis

The collected data underwent a dual analytical approach, encompassing both qualitative and quantitative methodologies. Information derived from focus group discussions and key informant surveys was subjected to qualitative analysis, employing a descriptive methodological framework. This analytical phase was specifically directed towards the precise calculation of pivotal parameters, including effective area, NTFP frequency and density, total fresh and dry growing stock, and annual allowable harvest (AAH) quantity.

Effective area (ha):

This metric denotes geographical areas where the targeted species is currently extant. The effective habitat (expressed in hectares) was estimated by integrating the potential habitat, as meticulously delineated from district and CFUG-level participatory resource mapping, with the species' frequency of occurrence (expressed as a percentage) obtained from plot-level inventory data.

Effective area (ha)=Potential habitat of species "A" (ha)×frequency of occurrence (%)

Frequency of occurrence: Frequency represents the proportion of sampling units in which a particular species is present, thereby reflecting its dispersion as a percentage of occurrence (Bonham, 1989; Raunkiaer, 1934)

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$$\text{Frequency (F)} = \frac{Total\ number\ of\ plots\ in\ which\ species\ \text{"A"}occured}{Total\ number\ of\ plots\ sampled} \times 100$$

Density: Density is rigorously defined as the total number of individuals of a given species per unit area, providing a quantitative measure of the species' numerical strength within a specific ecological community (McArdle, 2013).

$$\text{Density (plants/ha)} = \frac{\text{Total number of Individyals of species "A"}}{\text{Total number of quadrats sampled} \times \text{Area of quadrats } (m^2)} \times 10000$$

Growing Stock: Growing stock was estimated in terms of kilograms per hectare (kg ha^{-1}) and subsequently converted to total metric tonnes across the entire forest area. During the field survey, the fresh weight of samples was precisely measured from the field plots through a process of destructive harvesting. The corresponding dry weight was then estimated utilizing a predefined conversion factor (cf). The dry weight of a species, when multiplied by the Annual Allowable Harvest (AAH) factor, yields the AAH amount. AAH factors were applied as recommended by the ANSAB's participatory NTFPs inventory toolkit (ANSAB, 2010) and the NTFP inventory guideline of the Department of Forests, Government of Nepal (2012).

Results

Distribution and Occurrence

Field assessments across five districts revealed that *Nardostachys jatamansi* was present in all sampled alpine forest and meadow habitats, ranging between elevations of 3,300 m and 4,800 m. The species was found growing predominantly on moist north-facing slopes, alpine scrub zones, and near Rhododendron and Juniper thickets. Of the 500 inventory plots surveyed, *N. jatamansi* occurred in 64.7% of plots, indicating moderate spatial prevalence. Humla and Darchula districts showed the highest frequency of occurrence (73% and 71%, respectively), whereas Jumla and Mugu reported lower presence (56% and 58%), Fig 2.

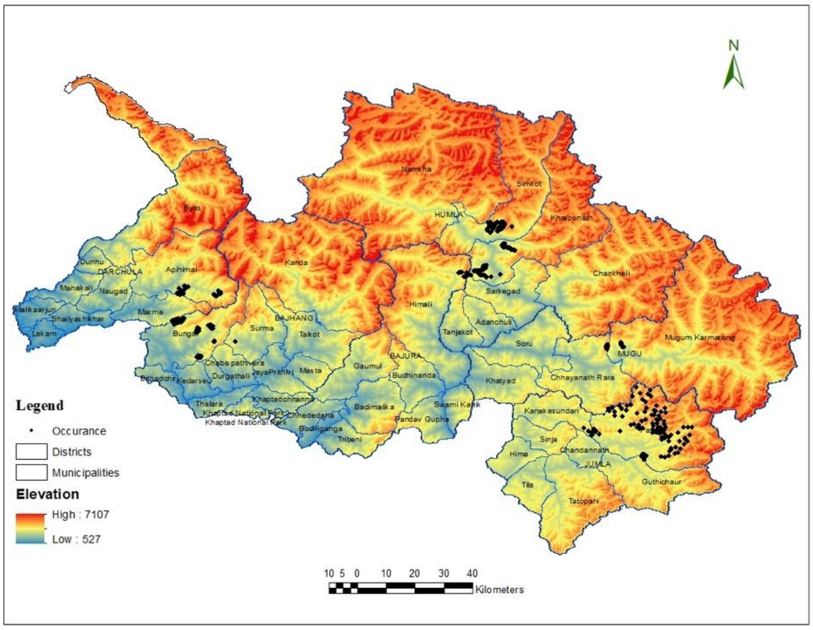

Fig. 2: Study area map showing occurrence points

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Density, Growing Stock, and AAH

The overall mean density of mature *N. jatamansi* plants was recorded at 331 individuals per hectare District-wise variation was significant (ANOVA, $p < 0.01$), Overall, dense forest areas consistently support higher regeneration and mature plant densities than sparse areas, highlighting the importance of canopy cover and favorable microclimatic conditions. The mean density of Jatamansi regeneration (≈678 plants ha^{-1}) being higher than that of mature plants (≈501 plants ha^{-1}) indicates active natural regeneration across the sites. This suggests that existing habitats remain ecologically suitable for species renewal. However, the lower density of mature plants may reflect past harvesting pressure, slow growth, or mortality before reaching maturity. The difference highlights the importance of regulating harvest intensity and protecting regenerating cohorts to ensure sustainable population structure. These findings are significant for community forest management, as they support the need for site-specific harvesting guidelines, regeneration monitoring, and conservation measures to maintain long-term productivity and ecological balance of Jatamansi populations.

District wise, Humla district, regeneration density in dense forests ranges from 722 plants ha^{-1} (Goraktu) to as high as 3,055 plants ha^{-1} (Sallikhola), while mature plant density reaches up to 1,606 plants ha^{-1} in the same forest. Similarly, Mugu district shows strong populations, particularly in Pangsarin, where regeneration density in dense forest is 3,041 plants ha^{-1} and mature plant density is 2,814 plants ha^{-1}, the highest recorded among all sites.

In contrast, Jumla, Bajhang, and Darchula generally exhibit lower densities. For example, dense regeneration in Jumla ranges from 344 plants ha^{-1} (Churkoti) to 1,320 plants ha^{-1} (Maharudra), while in Darchula it remains below 351 plants ha^{-1} in most forests. Sparse forest areas across all districts show markedly reduced densities, often less than half of dense forest values. Regenerating individuals (juvenile plants <2 years) accounted for 22–30% of populations, depending on microclimate and slope stability.

Table 2: Density of *N. jatamansi* in Mountain CFUGs

SN	District	Community Forest	Density of regeneration in Dense (ha)	Density of regeneration in Sparse (ha)	Density of mature plants in Dense (ha)	Density of mature plants in Sparse (ha)
1	Humla	Mauri	1200	467	758	327
2	Humla	Goraktu	722	235	376	149
3	Humla	Hilsa	1056	209	707	112
4	Humla	Thala	2196	698	1278	447
5	Humla	Thali	1570	1030	470	650
6	Humla	Takpafuk	2028	194	1188	123
7	Humla	Torpahutik	1553	596	562	443
8	Humla	Sallikhola	3055	376	1606	673
9	Humla	Gurgure	1304	411	707	559

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10	Mugu	Chulya	124	222	1049	80
11	Mugu	Chuwathopka	488	288	781	419
12	Mugu	Ladegaad	2824	71	1341	612
13	Mugu	Pangsarin	3041	607	2814	910
14	Mugu	Sherok	2232	763	1505	484
15	Jumla	Maharudra	1320	152	320	104
16	Jumla	Deuramai	368	147	463	221
17	Jumla	Churkoti	344	63	750	275
18	Jumla	Nadai	1288	224	1541	429
19	Bajhang	Khatkatde	1307	440	347	310
20	Bajhang	Juttebhadmaya	177	177	172	172
21	Bajhang	Yekchale	212	141	118	235
22	Bajhang	Liche	259	216	222	232
23	Bajhang	Panbhelbira	167	183	111	156
24	Bajhang	Chiurigad	1102	78	156	117
25	Darchula	Bhawanidhaula	221	28	290	97
26	Darchula	Siyaladigarful	141	54	173	65
27	Darchula	Surmabhawani	76	65	141	97
28	Darchula	Deulighat	195	156	68	146
29	Darchula	Kalimati	351	107	320	62

The mean growing stock (GS) and Annual Allowable Harvest (AAH) of Jatamansi across selected community forests in Humla, Mugu, Jumla, Bajhang, and Darchula districts, based on effective dense and sparse habitat areas. Humla district contributes the highest GS, with Mauri CF alone producing about 28.48 tons, reflecting its large effective area and high mean GS (293 kg ha^{-1}). Similarly, Thali, Thala, and Hilsa CFs also show substantial stocks, indicating favorable ecological conditions and relatively intact populations. Across all districts, GS from dense areas is consistently higher than from sparse areas, justifying the classification and highlighting the importance of conserving dense habitats. Jumla and Bajhang show moderate but stable GS levels, while Mugu and Darchula contribute comparatively lower stocks due to smaller effective areas and lower mean GS. The total GS values are systematically converted into AAH, generally set at around 40% of total GS, ensuring sustainability. The significance of these values lies in its practical application for sustainable harvesting planning. It provides a science-based justification for setting harvest quotas, prioritizing high-potential community forests, and regulating extraction pressure. The results support adaptive management, balancing livelihood benefits with long-term conservation of Jatamansi populations (Table 3).

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Table 3: Mean and total growing stock with AAH of Jatamansi

District	CF Name	Effective area in dense (ha)	Effective area in sparse (ha)	Mean GS (Kg ha^{-1})	GS in Dense (Kg)	GS in Sparse (Kg)	Total GS (Kg)	Total GS (Tonne)	Total AAH (Tonne)
Humla	Mauri	71.4	25.8	293.0	20927.5	7557.15	28484.65	28.48	11.39
	Goraktu	40.7	6.9	183.8	7477.13	1268.85	8745.98	8.75	3.50
	Hilsa	40.2	9.7	174.6	7016.40	1700.95	8717.35	8.72	3.49
	Thala	39.5	9.9	191.2	7546.37	1886.59	9432.96	9.43	3.77
	Thali	44.7	7.0	208.6	9328.83	1451.15	10779.98	10.78	4.31
	Takpafuk	28.3	6.5	133.0	3763.57	870.91	4634.48	4.63	1.85
	Torpahutik	9.9	1.0	131.6	1303.55	133.32	1436.87	1.44	0.57
	Sallikhola	21.9	9.7	112.32	2464.82	1088.36	3553.18	3.55	1.42
	Gurgure	32.2	9.8	104.18	3355.45	1016.80	4372.25	4.37	1.75
Mugu	Chuwathopka	40.1	6.0	117.02	4695.91	704.39	5400.30	5.40	2.16
	Sherok	24.5	5.3	94.02	2302.23	500.03	2802.26	2.80	1.12
	Ladegadh	12.2	1.4	109.01	1334.28	147.16	1481.45	1.48	0.59
	Chulya	22.8	3.9	106.24	2423.83	414.33	2838.16	2.84	1.14
	Pangsarin	18.0	4.9	60.08	1083.47	294.16	1377.63	1.38	0.55
Jumla	Maharudra	42.1	9.9	183.9	7737.68	1820.63	9558.31	9.56	3.82
	Deuramai	43.6	8.9	144.8	6308.94	1290.46	7599.40	7.60	3.04
	Churkoti	33.1	9.8	124.64	4122.57	1221.50	5344.08	5.34	2.14
	Nadai	21.8	5.5	74.77	1633.05	408.26	2041.31	2.04	0.82
Bajhang	Khatkatde	41.2	8.8	190.8	7866.81	1685.75	9552.56	9.55	3.82
	Juttebhadmaya	15.0	3.9	162.5	2442.45	634.40	3076.85	3.08	1.23
	Yekchale	3.0	1.0	127.6	380.55	130.24	510.79	0.51	0.20
	Liche	11.1	1.8	120.0	1331.04	218.02	1549.06	1.55	0.62
	Panbhelbira	33.2	3.7	132.4	4390.09	485.33	4875.43	4.88	1.95
	Chiurigaad	16.3	3.5	39.97	652.85	140.28	793.14	0.79	0.32
Darchula	Bhawanidhaula	20.9	2.4	72.4	1511.32	172.27	1683.58	1.68	0.67
	Siyaladigarful	26.7	4.1	79.4	2118.06	326.75	2444.82	2.44	0.98
	Surmabhawani	15.5	2.9	137.2	2129.50	402.67	2532.17	2.53	1.01
	Deulighat	25.4	4.8	133.6	3398.13	642.56	4040.69	4.04	1.62
	Kalimati	22.3	4.9	146.9	3272.26	713.95	3986.21	3.99	1.59
Total								**153.6**	**61.4**

The box and whisker plots were used to show the visual pattern of Jatamansi in the selected 29 CFUGs of Humla, Mugu, Jumla, Bajhang, and Darchula districts where the large data sets in terms of mean and median values have been presented. In addition, the extreme values were also plotted, which indicates the potential productivity of a particular species in the selected

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CFUGs of the study districts up to that optimum level if the forests and meadows are managed sustainably.

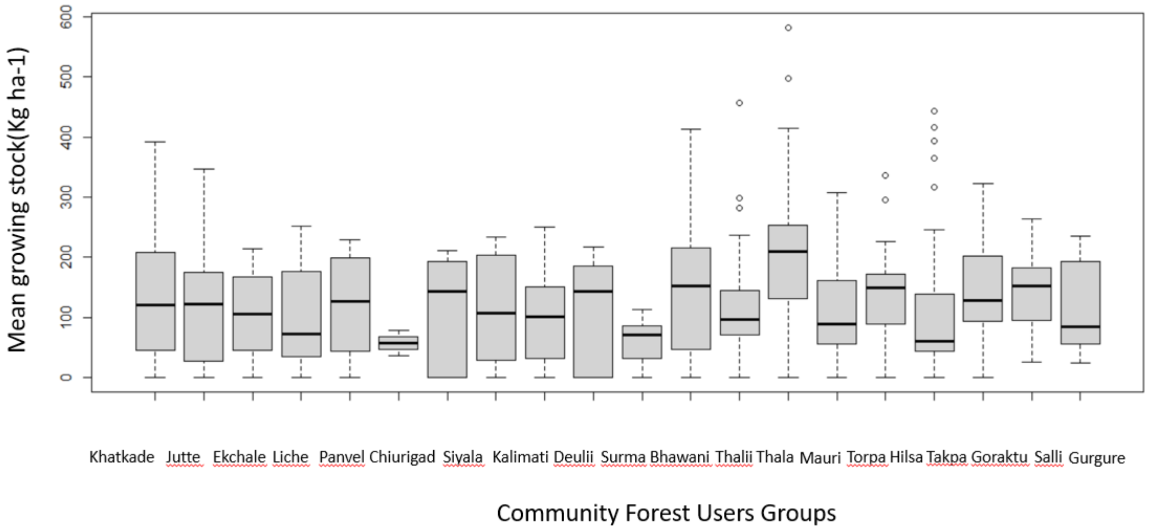

Fig.1: Box and whisker plot showing productivity and production potential of Jatamansi

Based on the above, Thali, Thala and Mauri, Takpafuk CFs of Humla has the highest spread of the Jatamansi production up to 600 kg per hectare, while that of minimum Jatamansi production was observesd in lowest (<100 kg ha^{-1}) in Chiurigad CF of Bajnag followed by Surmabhawani CF of Darchula.

Aspect and Elevational Correlations

The principal component analysis (PCA) graph principal component circle illustrates the relationships between Jatamansi yield across slope aspects using the first two principal components. Dimension 1 (31.99%) explains the largest share of variance and is positively associated with NE, SE, S, and SW yields, indicating higher productivity on relatively warmer and moderately moist aspects. Dimension 2 (20.18%) separates NW and N yields, reflecting cooler, moisture-retentive conditions that influence biomass differently. The longer vectors for NE yield and SW yield indicate stronger contributions to overall variability, while their angular separation suggests contrasting ecological controls among slope aspects. Overall, the plot highlights aspect-driven microclimatic effects on Jatamansi yield (Fig 4 and Fig 5).

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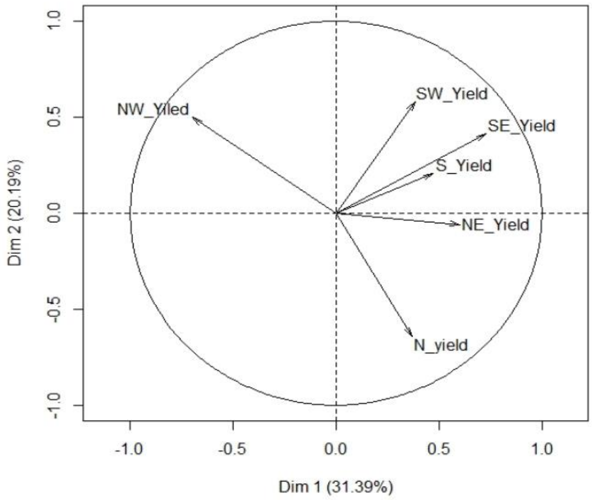

Fig.4: Aspect-wise principal component analysis for Jatamansi

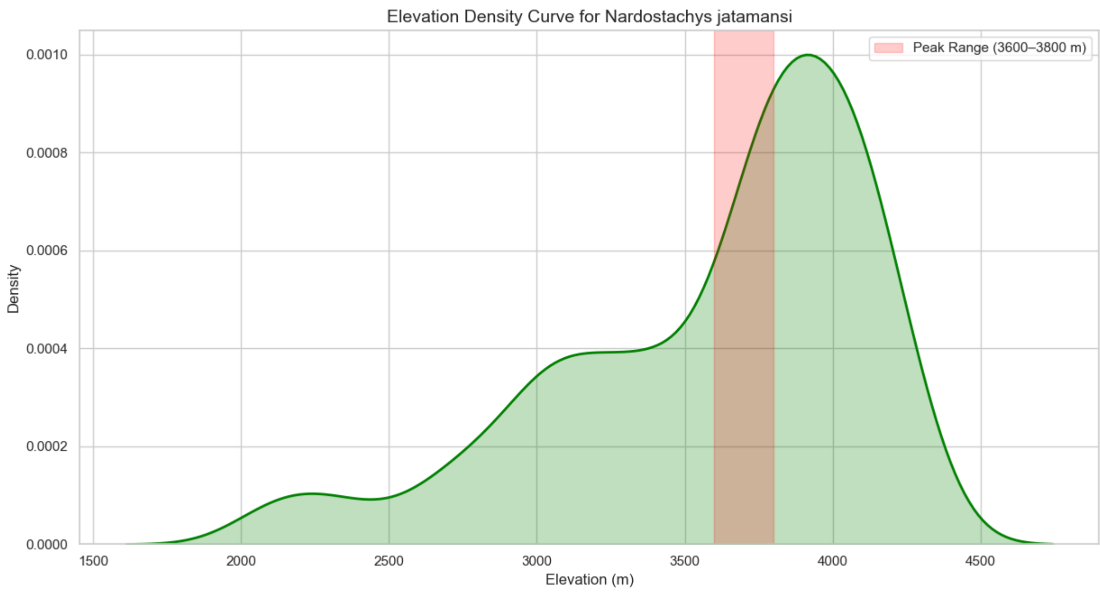

Fig.5: Elevation-wise principal component analysis for Jatamansi

The PCA loading scores, the 4000m+ elevation zone (X4000) is the primary driver of the first and most important principal component (Dim 1, 44.47%), with a strong positive loading of 0.80. This suggests conditions above 4000m are a major source of variation in Jatamansi productivity. Conversely, the 3700-3900m zone (X3700.3900) dominantly defines the second component (Dim 2, 23.35%) with a very high loading of 0.95, indicating it represents a unique and significant productive niche. The 3400-3600m zone contributes moderately to Dim 1 but is less influential, showing it is not a primary driver of the observed production pattern in the Alipne Meadows (Fig 6).

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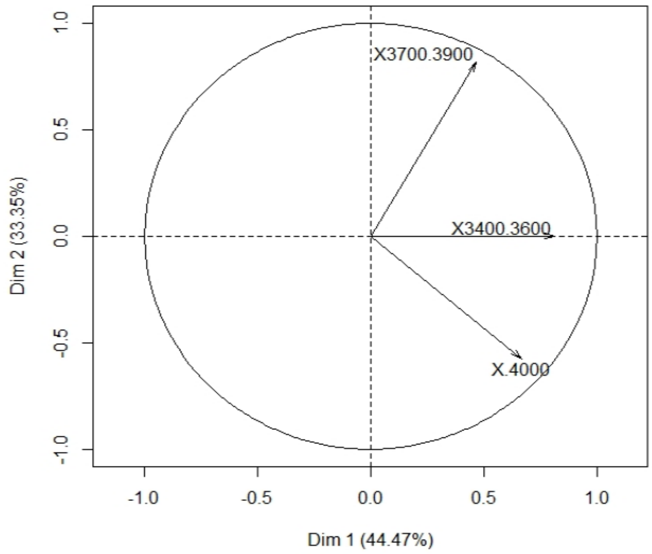

Fig.6: Elevation-wise principal component analysis for Jatamansi

Discussion

This study advances understanding of *Nardostachys jatamansi* DC by moving beyond simple documentation of distribution and use to reveal the demographic, ecological, and governance processes driving its continued decline in western Nepal. The findings collectively indicate that the species' Critically Endangered status is not an abstract classification, but the outcome of interacting biological constraints, climatic sensitivity, and institutional weaknesses.

Interpreting Low AAH in a Critically Endangered Context

The estimated Annual Allowable Harvest (AAH) of approximately 0.20 tonne is strikingly low, yet ecologically justified when interpreted in light of the species' life-history traits. *N. jatamansi* is a slow-growing, perennial alpine herb with limited vegetative spread and delayed sexual maturity. These characteristics, combined with regeneration rates of only 22–30%, severely constrain its capacity to recover following extraction. For comparable rhizomatous MAPs such as *Valeriana jatamansi* sustainable harvest thresholds typically range between 0.3 and 0.8 kg ha^{-1} under moderate regeneration conditions. The fact that *N. jatamansi* despite being Critically Endangered shows extraction levels exceeding 2.5 kg ha^{-1} in some CFUGs underscores the magnitude of the sustainability crisis. Although national NTFP guidelines prescribe uniform harvest rates, these results demonstrate that such blanket prescriptions are ecologically inappropriate for highly sensitive alpine species. The low AAH should therefore be interpreted not as a conservative anomaly, but as an early warning signal that current harvesting regimes are fundamentally misaligned with biological reality.

Regeneration Density Mismatch and Population Stability

Low regeneration rates gain deeper significance when synthesized with mature plant density data. The recorded mean density of 331 mature plants ha^{-1} is notably lower than the ~500 plants ha^{-1} reported by ANSAB (2014) from Dolpa, suggesting either regional depletion or a broader range-wide decline. More importantly, the weak representation of juveniles relative to mature individuals indicates a demographic imbalance characteristic of "senescing populations," where standing biomass masks imminent collapse. Under such conditions, even small increases in harvest intensity can trigger rapid population declines, particularly in alpine environments where recovery is slow and recruitment episodic.

Microclimatic Refugia and Climate Change Implications

The higher biomass observed on north- and northeast-facing slopes highlights the role of microclimatic refugia in sustaining *N. jatamansi* populations. These aspects provide cooler temperatures, higher soil moisture, and reduced evaporative stress, buffering the species against regional warming trends. Himalayan biodiversity assessments increasingly recognize such microrefugia as critical for alpine species persistence under climate change. However, their spatial limitation also implies heightened vulnerability: as suitable habitats contract upslope, harvesting pressure may intensify within these refugia, accelerating degradation unless proactively managed.

Market Dynamics, Governance, and Trade Collapse

The observed decline in trade volumes after 2016, despite rising prices, aligns with the "boom-and-bust" cycles described by Olsen and Helles (1997) for unregulated MAP markets. Rather than reflecting successful conservation, this downturn likely signals localized resource exhaustion combined with enforcement ambiguities. Continued informal trade, despite export bans, further erodes incentives for sustainable management, certification, or local processing. This governance paradox weakens both conservation outcomes and livelihood resilience.

Limitations, Enforcement Challenges, and Pathways Forward

While the AAH derived in this study is scientifically robust, its practical enforcement remains constrained by poverty, weak monitoring, and informal market structures. This limitation is not unique to *N. jatamansi* but reflects systemic challenges in Himalayan NTFP governance. Nevertheless, evidence from Nepal suggests that community-based monitoring, participatory harvest planning, and certification schemes such as FairWild can improve compliance and ecological outcomes when coupled with market incentives and technical support.

The decline of *N. jatamansi* is best understood as a coupled socio-ecological failure rather than isolated overharvesting. Addressing this requires species-specific harvest limits grounded in regeneration dynamics, protection of climate refugia, revitalization of biocultural stewardship, and institutional mechanisms that translate ecological knowledge into enforceable and equitable practice. Without such integrated action, even well-intentioned conservation policies will remain insufficient to halt the erosion of this iconic Himalayan medicinal plant.

Conclusion and Recommendation

Nardostachys jatamansi DC, is a high value and flagship medicinal and aromatic plant of the Nepal Himalayas, represents a complex nexus of ecological significance, fragility, cultural heritage, and livelihood opportunity. This study establishes a multidimensional baseline on its distribution, abundance, and socio-ecological importance, revealing both significant potential and serious conservation risks. Quantitative assessments across five high-altitude districts show that the species is ecologically restricted to narrow elevation bands (3,700–3,900 m), with productivity strongly influenced by slope aspect and microclimatic conditions. Although moderate standing growing stock and harvest potential exist, regeneration levels are critically low, indicating recruitment bottlenecks that threaten long-term population viability. Species distribution modeling (MaxEnt) further predicts climate-driven shifts in suitable habitats, highlighting the need for adaptive, forward-looking conservation approaches. Ethnobotanical evidence confirms the species' deep integration into Himalayan medicinal systems, spiritual practices, and subsistence economies, particularly in Karnali and Sudurpaschim provinces. However, weak governance and market distortions persist, including informal trade despite regulatory bans and limited capacity of Community Forest User Groups to implement sustainable harvesting or certification. Securing the future of *N. jatamansi* requires species-specific harvest protocols, community-based monitoring, climate-resilient habitat management, value-chain strengthening through local processing and certification, and integration of biocultural knowledge into conservation training. Reframing *N. jatamansi* as a socio-ecological asset rather than a mere commodity is essential for sustainable stewardship in fragile mountain ecosystem products and services.

Author Contribution

Nabin Raj Joshi: Conceptualization, Methodology, Investigation, Formal Analysis, Writing Original Draft, Project Administration Data Curation, Validation, Writing, Review & Editing.

Conflict of Interest

The author declare no conflict of interest.

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