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Population structure and regeneration of *Tsuga dumosa* and *Abies spectabilis* across altitudinal gradient in Rasuwa district, central Nepal

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In Nepal, *Tsuga dumosa* thrives well between 2,100–3,600 m altitudes above the mean sea level, mostly in the temperate region while *Abies spectabilis* occurs between 3,000–4,200 m altitude above the mean sea level in the sub-alpine region. Research on mature *T. dumosa*-*A. spectabilis* forests in Nepal is limited. This study aimed to analyze the population structure and regeneration status of *T. dumosa* and *A. spectabilis* in the high-altitude mixed forests of Rasuwa, central Nepal. Conducted in 2023, a total of 61 concentric circular sample plots were laid out following a stratified systematic sampling method. The population-structure-curve displayed a consistent upward trend showing abnormality. The abnormal population structure with a lack of young trees and poor regeneration status in both species points towards potential threats like grazing and wildfires. The highest DBH class ranged from 90 cm to 120 cm DBH for *T. dumosa* while from 60 cm to 90 cm DBH for *A. spectabilis*. The study found that the seedling condition of *T. dumosa* species was 'fair' in the lower (2800–3100 m) and middle stratum (3100–3400 m), while it was 'poor' in the upper-elevation stratum (3400–3600 m). On the other hand, the seedling condition of *A. spectabilis* was found to be 'poor' in all the three elevation strata. Furthermore, the sapling condition of both the species were found to be 'poor'. Therefore, the studied forest requires sustainable management along with a comprehensive strategy combining controlled grazing, zonation, monitoring, community engagement, regulation enforcement, restoration, ongoing research, and public awareness.

Keywords: Anthropogenic disturbance, conifer, climate change, grazing, high-altitude forest

High-altitude forests in Nepal offer various essential services, such as firewood, construction materials along with edible and medicinal plants, which are crucial for subsistence survival in challenging environmental conditions (Dhamala *et al*., 2020). The total forest area in the country has increased from 39.99% (5,915,518 ha) in 2000 to 41.69% (6,166,766 ha) in 2019 (FRTC, 2022). Forests act as natural carbon sinks, absorbing vast amounts of CO_2 from the atmosphere and playing a pivotal role in regulating global temperatures. However, they are under unprecedented threat from deforestation, degradation, and wildfires, exacerbating the climate crisis (IPCC, 2023). Community structure, composition, and vegetative function are pivotal ecological attributes of forests, exhibiting variations in response to both environmental and anthropogenic factors (Rana *et al*., 2020).

Climate change and anthropogenic disturbances are causing notable changes in the structure, composition, and regeneration of natural forests in the Himalayan region of Nepal. Temperatures are found to be increasing across Nepal, with an average yearly trend of 0.06°C, particularly

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noticeable in the elevated regions (Shrestha & Aryal, 2011). High-altitude forests in the Himalayas are susceptible to anthropogenic disturbances due to the harsh climatic conditions and the presence of local populations at high altitudes (Gairola *et al*., 2014). Anthropogenic disturbances like grazing, logging, and fuelwood collection are identified as major contributors to forest degradation in Himalayan ecosystems (Maren & Sharma, 2018). Most of the population structure and regeneration studies are reported from the Terai forests of Nepal (Chhetri *et al*., 2023). However, there remains a significant gap in understanding the regeneration dynamics of the forests across the elevation gradient in the Nepal Himalaya (Kharal *et al*., 2015). Research along these elevation gradients holds great importance due to the varied abiotic factors, such as temperature, which change significantly with altitude. Quantitative studies of high-altitude forest is crucial for assessing the impact of climate change on future species coexistence, establishing baseline data for long-term monitoring, and understanding species shifts (Dash *et al*., 2021).

Gymnosperms, particularly conifers, are important vegetation of Nepal. Nearly all the conifer species in Nepal ranges from subtropical to sub-alpine regions (Rajbhandari *et al*., 2020). *Tsuga dumosa* is one among the 41 conifer species found in Nepal. Commonly known as 'Himalayan hemlock', it generally occurs between 2,100–3,600 m altitudes above the msl in the temperate region of Nepal (Jackson, 1994). *T. dumosa* occurs on the southern slopes in the eastern Himalayas from Kumaon (80°E) to the Inner Valleys (84°E) with pure stands common between 2,100–3,000 m (Miehe *et al*., 2015). *T. dumosa* accounts for approximately 7.68% of the High Mountain and High Himal forests of Nepal, with the growing stock of 17.86 m^3 per ha . Similarly, *Abies spectabilis,* commonly known as 'Himalayan silver fir', predominates in the moist, high-altitude forests near the upper tree line across the western Himalayan region (DFRS, 2015). This species is found in both humid and sub-humid conditions in the upper montane belt, ranging from Kumaon to Eastern Nepal. *A. spectabilis* forests is commonly found between 3,000–4,200 m in the sub-alpine region (Miehe *et al*., 2015). *Abies* species comprise about 10.15% of the total stem volume, amounting to 23.58 m^3 per ha in High Mountain and High Himal forests of Nepal (DFRS, 2015). On the other hand, the high-altitude forests of the Nepalese Himalaya, especially those composed of mixed *T. dumosa-A. spectabilis* forests, remain relatively understudied ecosystems. To date, only a few studies have examined the community structure and regeneration of *A. spectabilis* in Nepal (Tiwari, 2010; Kharal et al., 2015; and Nagarkoti et al., 2019). However, there has been no research conducted on mature *T. dumosa-A. spectabilis* forests in Nepal. The objective of this study was to examine the population structure and regeneration status of *T. dumosa* and *A. spectabilis* in the high-altitude mixed forest of Rasuwa, central Nepal. The main research questions addressed for the purpose of this study were: i) how does the population structure of mixed *T. dumosa* and *A. spectabilis* differ in comparison to other species? and ii) do the regeneration patterns of both *T. dumosa* and *A. spectabilis* significantly vary across different elevation strata? Therefore, quantitative assessments of tree communities are also essential for sustainable utilization, management, and conservation of species within specific forest communities (Rawat *et al*., 2018).

Materials and methods

Study area

The study was conducted in Jyarsogothen community forest, situated in Aamachhodingmo Rural Municipality-03, Gatlang within Rasuwa district, located in the central Himalayan region of Nepal (see Figure 1) in 2023. Situated within the Bagmati province, the district is adjacent to the Tibetan autonomous region of China. It is located between 27⁰55'–28⁰25' N latitudes and between 85⁰00’–85⁰50' E longitudes, with an altitude ranging from 614 m to 7227 m above the mean sea level (msl) (Dong, 2017). The district possesses 49,821 ha (33.19%) forest area and 4,935 ha (3.29%) of other wooded land. The forest area covers most of the Langtang National Park (LNP) and a portion of the Chitwan-Annapurna Landscape (CHAL). The terrain of the study area ranges from 2600 m to 3700 m above the msl.

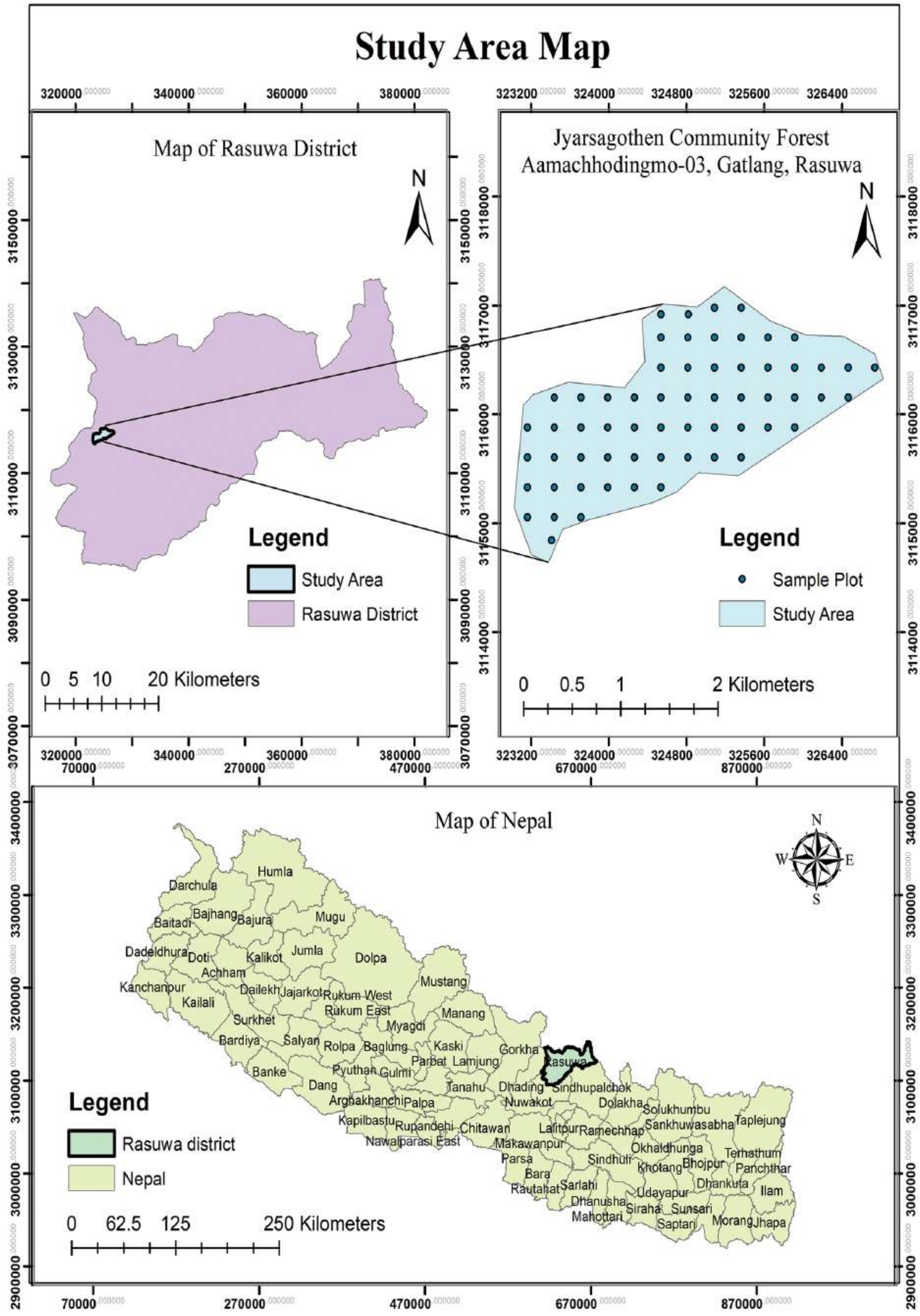

Figure 1: Location of the study area in Rasuwa district, central Nepal and the layout of sample plots within the study area (upper right corner).

The elevation gradients, in conjunction with complex topography and geology, have engendered a diverse array of biodiversity and distinct vegetation belts. In the temperate zone (2600–3000 m), oak forests are dominant, transitioning into old-growth forests of *A. spectabilis, T. dumosa*, and *Larix himalaica* in the lower sub-alpine zone (3000–3600 m). Near the tree line, species like *Betula utilis, A. spectabilis, Sorbus microphyla*, and *Rhododendron campanulatum* are commonly found (Chaudhary, 1998). The study site had significant anthropogenic disturbance, primarily due to the logging activities targeted towards *A. spectabilis* and Rhododendron species, especially for timber and firewood. Besides, yak & sheep herding system was reported to be common in and around the study site, with around 1500 yaks and sheep per annum; grazing being concentrated during March–October. The study site exhibits a typical temperate climate with snowfall in winter and cool temperatures in the remaining seasons. The average annual rainfall is 691.7 meters, with most of it occurring during the monsoon season (June–September) (DHM, 2022). The district is home to several renowned religious and tourist wetlands, including Gosaikunda and Parvatikunda. The study site receives snowfall during the winter season, making it an attractive destination for tourists and researchers.

Sampling design

After conducting a reconnaissance survey to identify the natural distribution range of *T. dumosa* and *A. spectabilis* dominant forests, the whole forest (omitting the fire burnt area) was categorized into three distinct strata based on altitudinal variation: i) lower- elevation stratum (2800–3100 m) denoted by symbol 'A', ii) medium-elevation stratum (3100–3400 m) denoted by symbol 'B', and iii) upper-elevation stratum (3400–3600 m) denoted by symbol 'C'. A total of 61 concentric circular sample plots (CCSPs) were established systematically within the study area, i.e. the community forest using a two-dimensional fishnet approach in accordance with the Community Forest Inventory Guidelines, 2004 (DOF, 2004). The sample plots were allocated proportionately in all three strata on the basis of their area coverages so as to ensure representative sampling across all the strata within the study area (see Figure 1). The aforementioned methodology was also adopted by Chikanbanjar *et al*. (2020). Table 1 below depicts the stratum-wise distribution of sample plots within the community forest:

Table 1: Stratum-wise allocation of sample plots

S. N.	Elevation category	Elevation range (m)	Area (ha)	No. of sample plots	Spacing among the sample plots (m)
1.	Lower (A)	2800–3100	166	22	275
2.	Middle (B)	3100–3400	136	18	275
3.	Upper (C)	3400–3600	158	21	275
	Total	**-**	**460**	**61**	**-**

The plots within the lower-elevation stratum were located near the seed stand established by the Division Forest Office, Rasuwa. Similarly, the plots within the middle-elevation stratum were located from 'Mendo-kharka' up to 'Uri-kharka'. Likewise, the plots within the upper-elevation stratum were located above the 'Uri-kharka' area of the community forest.

Data collection

In course of the measurement of sample plots, the diameters (DBH) of all the trees (DBH ≥ 30 cm) and poles (10–30 cm DBH) falling within the plots were measured and recorded. Besides, the number of saplings (> 100 cm ht. & < 10 cm DBH) and seedlings (30–100 cm ht.), representing the early stages of tree growth inside the plots, were also counted and documented.

Data analysis

The population structure was developed for the dominant species, i.e. *T. dumosa* and co-dominant species, i.e. *A. spectabilis* using the DBH information of the individual trees recorded. The data so recorded were entered, coded, validated and verified to rectify the errors. Data cleaning procedures, such as removing duplicates or outliers, were conducted to improve the data quality. Microsoft Office Excel (2019) was used to present the data in descriptive statistics form, i.e. column chart showing the trend line. IBM SPSS Statistics 23 was used to employ the one-way analysis of variance (ANOVA) to test whether there were statistically significant variations in the mean seedling and sapling densities among the three elevation strata.

The natural regeneration statuses of the dominant and co-dominant species recorded in the inventory were examined following the Community Forestry Inventory Guideline (2004). According to the CF Inventory Guidelines (2004), a forest is considered to be in 'good' condition if there are more than 5,000 seedlings and 2,000 saplings per hectare. If the numbers of seedlings and saplings fall between 2,000–5,000 and 800–2,000 per hectare, respectively, the forest is considered to be in 'medium' condition. A forest is deemed to be in 'poor' condition if the numbers of seedlings and saplings are less than 2,000 and 800 per hectare, respectively (DOF, 2004).

Results

Population structure

The population structure of the dominant species, i.e. *T. dumosa* indicated that the large proportion of its population consisted of the trees with higher DBH classes (90–120 cm and >120 cm); in the lower elevation stratum (2800–3100 m), denoted by symbol 'A' (Figure 2), its population density was observed to have increased continuously up to 90–120 cm DBH class while the trend was noticed to have decreased in the case of the trees with more than 120 cm DBH. The similar pattern of population structure was found in the middle elevation stratum (3100–3400 m), denoted by symbol 'B', too; however, the higher DBH class population was found to be less in the upper elevation stratum (3400–3600 m), denoted by symbol 'C', as compared to the other two elevation strata.

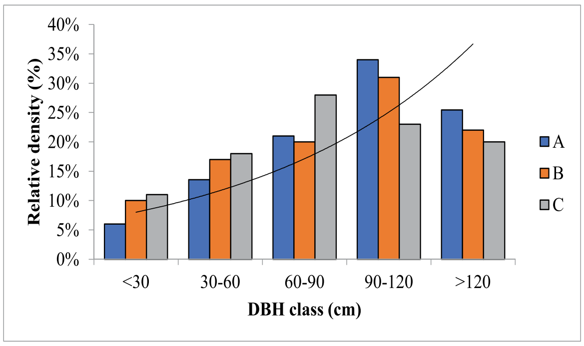

Figure 2: Population structure of dominant tree species (*T. dumosa*) across altitudinal gradient.

On the other hand, the population of the co-dominant tree species, *A. spectabilis* was found to be increasing up to the 60–90 cm DBH class in both the lower and upper elevation strata, indicated by symbols 'A' and 'C', respectively, but there was a slight decline in the population of the individuals falling under the lower DBH class (30–60 cm) in the middle elevation stratum, denoted by symbol 'B' (Figure 3); however, its population was found to have slightly increased again in the 60–90 cm DBH category in the same elevation stratum. Similarly, the population of the individuals falling under the 90–120 cm DBH class were observed to have increased slightly in the lower elevation but drastically in the middle elevation stratum; however, it was noticed to have declined again in the upper elevation stratum. The highest population of mature trees falling under the 90–120 cm category was noticed in the middle elevation stratum followed by the lower elevation and the upper elevation strata, respectively. The population of the individuals with more than 120 cm DBH was found to have decreased in all the three elevation strata.

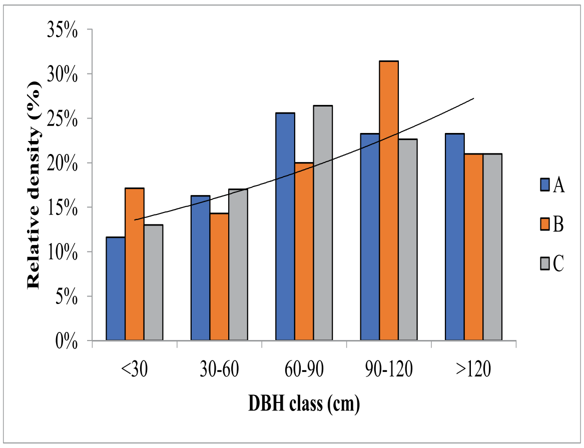

Figure 3: Population structure of co-dominant tree species (*A. spectabilis*) across altitudinal gradient.

Regeneration

The distribution of dominant and co-dominant species across different stages of growth, including seedlings and saplings differed across varying altitudes. Considering the compositional attributes, seedling density of *T. dumosa* decreased continuously with increasing altitude, whereas high accumulation of seedlings of *A. spectabilis* was found in the middle elevation. Variation in the seedling density across the three elevation strata was found to be significant (F=2.45 & p<0.01). Likewise, its seedling density was found to be in the 'medium' condition in the lower and middle elevation strata, but was 'poor' in the upper stratum. On the other hand, higher number of seedling individuals of *A. spectabilis* was found in the middle elevation followed by the upper and lower elevation strata, respectively. Its seedling density was found to be 'poor' in all the three elevation strata (Figure 4). Variation in the seedling density of *A. spectabilis* across the altitudinal gradient was significant (F= 6.40 & p<0.001) (Table 3).

Similarly, the sapling density of *T. dumosa* was highest in the lower elevation followed by the middle and upper elevation, respectively; however, the sapling density of *A. spectabilis* was greater in the middle elevation followed by the upper and lower elevation, respectively (Figure 5). Considering the compositional attributes, the variation in the sapling density of *T. dumosa* across the altitudinal gradient was found to be significant (F= 27.52 & p<0.001). Likewise, the variation in the sapling density of *A. spectabilis* across the altitudinal gradient was also found to be significant (F= 7.93 & p<0.001, Table 3). The sapling conditions of both the species were found to be in 'poor' state as per the CF Inventory Guidelines (2004).

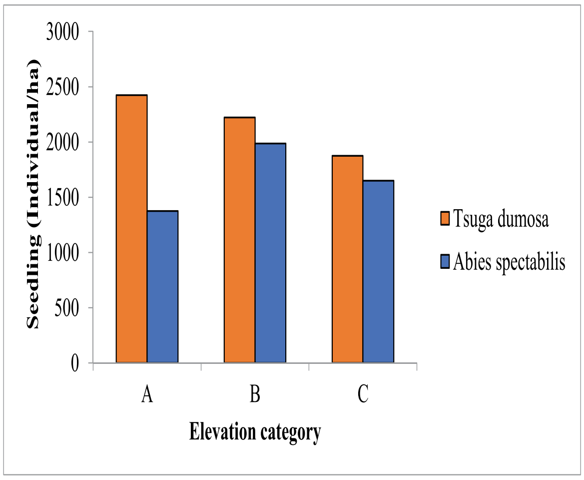

Figure 4: Seedling density of dominant and co-dominant tree species along altitudinal gradient.

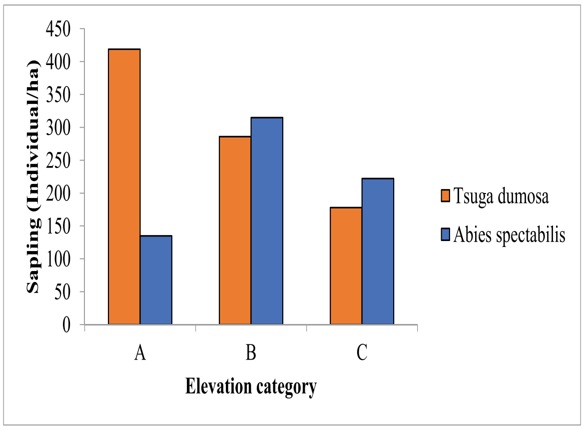

Figure 5: Sapling density of dominant and co-dominant tree species along altitudinal gradient.

Table 3: Summary of regeneration structure of *T. dumosa* and *A. spectabilis* across altitudinal gradient

S. N.	**Elevation stratum**	**Seedling density (no/ha)**		**Sapling density (no/ha)**	
		T. dumosa	***A. spectabilis***	***T. dumosa***	***A. spectabilis***
1.	2800–3100 m	2425	1375	419	135
2.	3100–3400 m	2222	1985	286	315
3.	3400–3600 m	1875	1650	178	222
F ratio		2.45*	6.40***	27.52***	7.93***

Significance levels: p <0.01* and p <0.001***

Discussion

The population structure of both *T. dumosa* and *A. spectabilis* revealed the higher proportion of their population falling in the DBH classes of 90–120 cm and 60–90 cm, respectively, with fewer populations falling in the lower DBH classes (30–60 cm and 60–90 cm), indicating the asymmetrical pattern of regeneration. Shrestha *et al.* (2007), Ghimire *et al.* (2008), and Qiaoying *et al.* (2008) reported a similar trend. The deviation of the *T. dumosa* and *A. spectabilis* curves from the typical reverse J-shaped size distribution, where larger trees dominate and smaller trees are fewer, indicated challenges in sustainable regeneration. The reason behind the abnormal curve might be due to anthropogenic disturbances such as logging, grazing, and trampling which can disrupt natural regeneration processes by damaging seedlings and saplings, hindering their growth and survival. Himalayan forests play a crucial role in nature conservation, and sustain the livelihoods of people living in the mountain regions (Dhamala *et al*., 2020); hence, over matured trees should be harvested applying the suitable silvicultural system which could also promote regeneration potential of the species. When looking at the individual DBH class, gaps were observed in some diameter classes. These gaps might be due to the past anthropogenic disturbances or episodic regeneration events. Anthropogenic disturbances could include human activities such as logging, clearing, or grazing, which can impact the growth and survival of trees (Burgess *et al*., 2022). Episodic regeneration events could include natural disturbances such as landslides or fires, which can create gaps in the forest canopy (Crausbay & Martin, 2016). The study documented a maximum DBH of 240 cm for *T. dumosa*, which is more than double the average weighted DBH of 100.88 cm for this species (DFRS, 2015). Similarly, the study identified a maximum DBH of 130 cm for *A. spectabilis*, surpassing the previously recorded maximum DBH of 120 cm in Sagarmatha National Park by Nagarkoti *et al.* (2019). Additionally, the study found that the density of trees with larger girth size was higher than that of the trees with smaller girth size throughout the *T. dumosa* dominated mixed-forest.

The seedling densities of both *T. dumosa* and *A. spectabilis* were found to be higher than their sapling densities, which indicated a normal demographic development. Both the species had a noticeable variation in their sapling distribution patterns between different elevations (see Figure 5 above). In a healthy forest ecosystem, there are usually more seedlings than saplings, as young regeneration are constantly germinating and growing, while some of the saplings may not survive to reach maturity stage. The average seedling density of *T. dumosa* was found to be higher in the lower elevation stratum followed by the middle elevation stratum and minimal in the upper elevation stratum. Furthermore, the average seedling density of *A. spectabilis* was appreciable in the middle elevation stratum which is analogous to the results of Kharal *et al.* (2015). The sapling density of *T. dumosa* was significantly different across the altitudinal gradient, with maximum density in the lower elevation stratum. Conversely, the sapling density of *A. spectabilis* was found higher in the middle elevation stratum followed by the upper elevation stratum and inconsiderable in the lower elevation stratum which corresponds with the findings of Kharal *et al.* (2015). Likewise, Chhetri *et al.* (2023) found the forest in a good regeneration condition in the tropical region of Nepal, but our study found the seedling condition of *T. dumosa* species in 'medium' condition in the lower and middle elevation strata, while it was in a 'poor' state in the upper elevation stratum. On the other hand, the seedling condition of *A. spectabilis*, as per the CF Inventory Guidelines (2004), was deemed to be in a 'poor' state in all the three elevation strata. The reason behind the 'medium' and 'poor' conditions might be due to harsh climatic conditions characterized by low temperature and moisture availability, which makes slow growth rate of regeneration (Dolezal *et al*., 2016). In the studied forest, grazing & trampling intensity was relatively high due to yak herding system. Grazing has a significant influence on the composition of tree seedling species (Darabant *et al.,* 2007). Tiwari (2010) found similar findings on *A. spectabilis* in the Langtang National Park. The variation in the seedling and sapling densities observed along the elevation gradient may be attributed to variations in soil nutrients and other abiotic factors, as well as climatic factors (Joswig *et al.,* 2022). Additionally, soil properties such as nutrient availability and water-holding capacity may also vary with elevation. Other factors may have contributed to the observed variation in adult densities across the elevation gradient, such as competition with other vegetation, the presence of pests and diseases, and human disturbances (Lindenmayer & Laurence, 2017). Therefore, further research may be necessary to determine the relative importance of different factors in influencing tree densities along the elevation gradient.

Conclusion

This study aimed to investigate the population structure and regeneration dynamics of *T. dumosa* and *A. spectabilis* in the high-altitude mixed forest of Rasuwa district, central Nepal. The study observed increasing trend of trees in larger DBH classes which showed a potential consequence of anthropogenic disturbances, resulting in an imbalance in population structure and a decrease in the population of younger trees within the ecosystem. This highlights the need for effective management strategies to mitigate the impacts of anthropogenic disturbances and promote the regeneration of forest, ensuring the sustainability of all stages of tree population. Effective management strategies to mitigate the impacts of anthropogenic disturbances and promote forest ecosystem regeneration include implementing controlled grazing practices, establishing buffer zones, conducting regular monitoring and assessment of forest health, engaging local communities in conservation efforts, enforcing regulations, restoring degraded areas through reforestation/afforestation and other conservation measures, collaborating with the concerned stakeholders, raising public awareness against haphazard grazing practices, investing in research and innovation, adapting management strategies based on changing environmental conditions & emerging threats, and so on. Such management efforts can be optimized through collaborative initiatives involving the appropriate technical staff of the division forest offices and the community forest user groups concerned.

Acknowledgments

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Author's contribution

The concept and design were developed and manuscript written by B. P. Dhungana and V. T. Chhetri

Data availability

The data that support the findings of this study are available upon request from the corresponding author.

Conflict of interest

The authors declare no conflict of interest

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