

Regeneration dynamics in Sal (*Shorea robusta*) forests under the shelterwood system

✉ Ram B. Thakur^{1,*}, ✉ Rajesh K. Rai², ✉ Ridish K. Pokharel³, ✉ Prem R. Neupane⁴

¹Office of the Dean, Institute of Forestry, Tribhuvan University; Kathmandu 44613, Nepal.

²School of Forestry and Natural Resource Management, Institute of Forestry, Tribhuvan University, Kathmandu 44613, Nepal.

³Independent Researcher-Freelancer, Kathmandu 44620, Nepal.

⁴World Forestry, Institute of Wood Sciences, University of Hamburg, Hamburg 20148, Germany.

*Correspondence should be addressed to Ram B. Thakur: rbthakur@gmail.com

Abstract

Aim of study: Critics of the shelterwood system claim that regeneration felling in mature stands reduces plant species richness and promotes a monospecific dominance of Sal (*Shorea robusta* Gaertn. f.). In this context, the study aims to evaluate the regeneration dynamics in Sal forests following regeneration felling.

Area of study: The study was conducted in the Sal forests of Nepal's lowland, where a series of regeneration felling were implemented under the shelterwood system.

Material and methods: A total of 270 rectangular plots, each measuring 10m², were established across 90 annual felling plots, with three sample plots allocated per felling plot. Within each sample plot, seedlings and saplings were measured and counted.

Main results: Light demanding species dominated both seedling and sapling layers, comprising 83% and 92% of the overall density, respectively. The diversity index was higher in the seedling layer (0.80) compared to the sapling layer (0.24). Since the most degraded plots were treated first, no clear trend in regeneration diversity and species richness was observed across the age groups (1-3 years, 4-6 years, and 7-9 years after harvesting).

Research highlights: Gap promoted the regeneration of light-demanding species initially, and plant species richness increased over time following regeneration felling. As seedlings grew into saplings and provided shade, shade-tolerant species gradually began to appear. Therefore, species richness was influenced by the time elapsed since regeneration felling.

Keywords: diversity index; harvesting; regeneration species richness; saplings; seedlings

Dinámicas de regeneración en bosques de Sal (*Shorea robusta*) bajo el sistema de aclareo progresivo

Resumen

Objetivo del estudio: Los críticos del sistema de aclareo progresivo sostienen que la corta de regeneración en masas maduras reduce la riqueza de especies vegetales y favorece una dominancia monoespecífica de Sal (*Shorea robusta* Gaertn. f.). En este contexto, el estudio tiene como objetivo evaluar las dinámicas de regeneración en los bosques de Sal tras la corta de regeneración.

Área de estudio: El estudio se llevó a cabo en los bosques de Sal del Terai (las tierras bajas de Nepal), donde se implementó una serie de cortas de regeneración bajo el sistema de aclareo progresivo.

Materiales y métodos: Se establecieron un total de 270 parcelas rectangulares, cada una de 10 m², distribuidas en 90 parcelas anuales de corta, asignando tres parcelas de muestreo por cada parcela de corta. En cada parcela de muestreo se contaron y midieron las plántulas y los brinzales.

Principales resultados: Las especies heliófitas dominaron tanto la capa de plántulas como la de brinzales, representando el 83% y el 92% de la densidad total, respectivamente. El índice de diversidad fue mayor en la capa de plántulas (0.80) en comparación con la de los brinzales (0.24). Dado que las parcelas más degradadas fueron tratadas primero, no se observó una tendencia clara en la diversidad de la regeneración ni en la riqueza de especies entre los distintos grupos de edad (1–3 años, 4–6 años y 7–9 años después del aprovechamiento).

Aspectos destacados de la investigación: Las aperturas favorecieron inicialmente la regeneración de especies heliófitas, y la riqueza de especies vegetales tendió a aumentar con el tiempo tras la corta de regeneración. A medida que las plántulas crecieron y se convirtieron en brinzales que generaron sombra, comenzaron a establecerse especies tolerantes a la sombra. Por tanto, la riqueza de especies estuvo influenciada por el tiempo transcurrido desde la corta de regeneración.

Palabras clave: brinzales; cosecha; índice de diversidad; plántulas; riqueza de especies en regeneración.

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Introduction

The shelterwood system aims to continue forest cover, ensuring adequate regeneration after felling mature trees. This system involves harvesting of mature trees in different phases, retaining a portion of canopy to facilitate natural regeneration, supplying seeds and protecting regeneration providing shelter (Raymond et al., 2009). Once natural regeneration is established, tending operations are conducted to promote the growth of individual plants, ensuring their quality and vigour. The success of regeneration is influenced by various factors, such as availability of viable seed source, competition with grasses and shrubs, and protection from external factors such as grazing and fire (Tyagi et al., 2011; Awasthi et al., 2015). The retained trees serve a dual purpose, providing both seed production and shelter for regeneration.

In Sal (*Shorea robusta* Gaertn.f.) forests, the shelterwood is considered as an appropriate silvicultural system, as natural regeneration is the most effective way to regenerate Sal (Jackson et al., 1994; Rautiainen & Suoheimo, 1997). This is the most valuable timber species in the Hindukush Himalayas, highly preferred for construction and recognized for its significant ecological importance (Timilsina et al., 2007). The shelterwood system is well-suited for species with longer regeneration periods, as it provides adequate light through gradual canopy opening, making it more effective than other silvicultural systems (Paudel et al., 2017). As Sal is a light demanding species, canopy opening and establishment of gaps in the forest significantly affect regeneration (Sharma et al., 2019; Zhu et al., 2014). A change in canopy cover alters the microhabitat within the forest, affecting sunlight and soil moisture, which in turn promotes the growth and survival of regeneration within a few years (<10 years) following seeding felling (Jennings et al., 1999; Trottier-Picard et al., 2014). This ultimately influences species composition of the stands under seeding/regeneration felling (Zollner & Crane, 2003).

Cutting intensity in the shelterwood system affects light transmission by gradually opening the canopy (Raymond et al., 2009). This means regeneration density varies with the density of shelter trees. An optimal number of shelter trees promotes regeneration, whereas overly dense or absent shelter trees hinder it (Rautiainen & Suoheimo, 1997). Shelter trees will not only provide low-light conditions but also encompass a variety of environmental factors such as temperature, humidity and nutrition with diverse effects on plants (Valladares et al., 2016). In Sal forests, the gradual opening of the canopy over multiple years enhances seedling density and species richness. But, repeated harvesting operations within the same plot may increase the risk of seedling damage during felling (Sapkota et al., 2009), which can influence species composition and

dominance in the regeneration layer. As a result, the structure of regeneration layer varies depending on the year following harvesting (Botroh et al., 2023).

The existing studies on assessing the effect of irregular shelterwood system on regeneration of Sal forests mainly compare the density and plant species richness at regeneration layer comparing managed and unmanaged blocks (Awasthi et al., 2015; Pokhrel et al., 2024). These studies have shown an increase in regeneration density but a decrease in species richness based on the cross-sectional data. The shelterwood approach has faced criticism for prioritizing short-term objectives over long-term biodiversity goals (Aryal et al., 2023). Therefore, it is essential to understand the long-term effects on plant species diversity (Awasthi et al., 2015).

The general objective of this study is to investigate species dynamics within regeneration layers of varying ages. The specific objectives include: (i) analysing changes in species composition over time, particularly in relation to the years following harvesting; and (ii) evaluating differences in species composition between seedling and sapling layers. This study hypothesizes that species composition in regeneration layers change over time, with light-demanding species dominating immediately after harvesting or in the sapling layer. Given that regeneration/seeding felling is implemented over nine-year period, this study includes an inventory of plots within the regeneration layers. It assessed regeneration density, species richness, dominance index, and similarity index for both seedlings and sapling layers to determine whether species composition changes over the time.

Material and methods

Study area

This study was conducted in the natural Sal (*Shorea robusta* Gaertn. f.) forests within the Tilaurokot Partnership Forest Management area in Kapilvastu, Nepal. A forest in which more than 60% percent of the basal area is composed of Sal trees is referred to as a Sal Forest (DFRS and FRA/DFRS, 2014). The forest is located in Nepal's Terai region, characterized by a Tropical Monsoon Climate, at an elevation ranging from 200 to 300 m above mean sea level. It covers an area of 6,612 hectares, with 22,622 households (a population of 148,631) as its users.

The forest is divided into two main parts, norther and southern part. According to the Tilaurokot CFM (2011), clay soil dominates the southern part of forest without any water logging condition. This means soil is well aerated, which is considered appropriate for natural regeneration in Sal forests (Tyagi et al., 2011). Sal grows on a variety of soil types but does not grow well in waterlogged, sandy, or gravelly soils (Suoheimo, 1998). The local communities and the government jointly manage the forest.

Sal forests cover 15% of the total forest area in Nepal and shares 19% of the total stem volume (DFRS, 2015). This is the first forest in Nepal to have adopted an irregular shelterwood system that started during 2011/12. Rotation period has been determined as 80 years with a regeneration period of 10 years. The establishment period was considered as the regeneration period for the Sal species (DoF, 2014).

The southern part is further divided into five blocks with natural boundaries (Figure 1). These blocks are further divided into 13 compartments, which are self-contained. This means each compartment is treated as an independent forest stand, where shelterwood harvesting method is applied in a phased manner to ensure a continuous cycle of regeneration, tending and harvesting. The reasons for dividing a block into different compartments are to minimize the size of the felling area and create diverse forest mosaics. The diverse forest structure and composition at stand and landscape level contribute to increased biodiversity and habitat creation for different wild animals (Charbonnier et al., 2016).

These compartments are further sub-divided into sub-compartments, with each compartment containing eight sub-compartments, also referred to as periodic blocks. Each sub-compartment undergoes regeneration/seeding felling for 10 years, resulting in a regeneration period of 10 years. In Tilaurokot forest, only 10 compartments or 80 sub-compartments have adopted the irregular shelterwood system. This means 10 sub-compartments of different compartments have regeneration felling operations. The area of the annual regeneration felling plot was determined based on the number of stems larger than 30 cm in diameter at breast height (dbh). Since felling operations are conducted for only nine years, the total number of annual felling plots in the given compartment is 90.

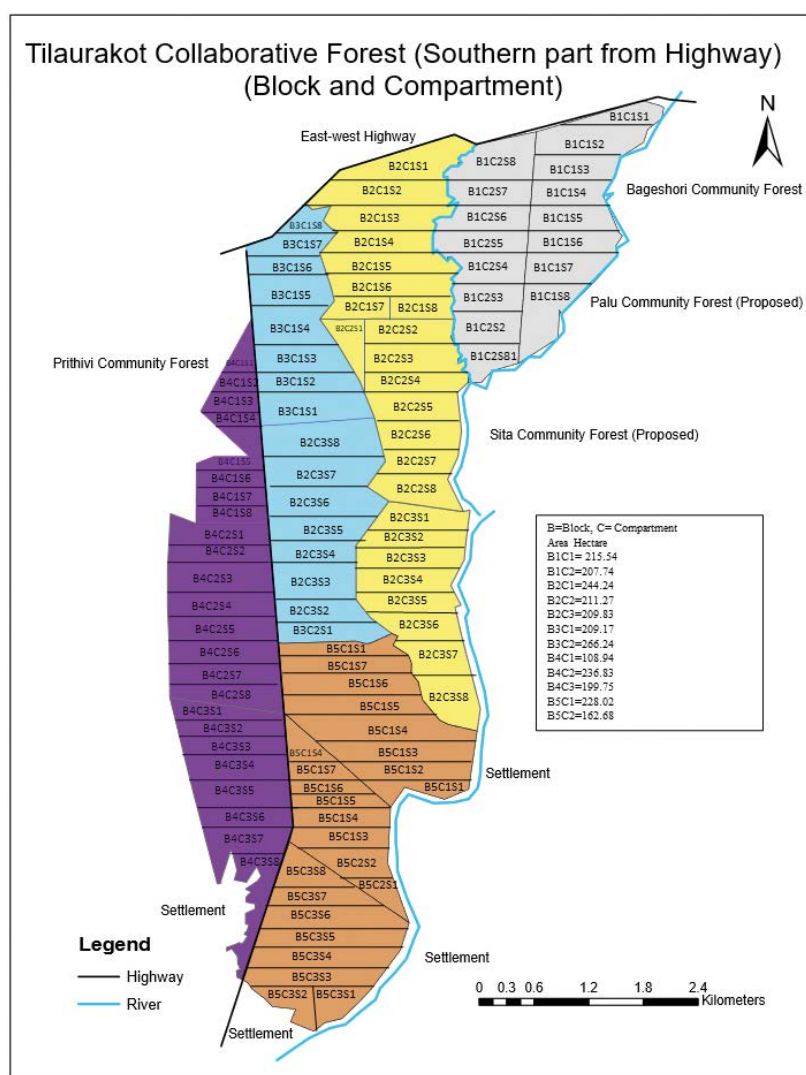


Figure 1. Map of the study area in the Sal forests of Nepal's lowland showing the division into Blocks (B), Compartments (C), and Sub-Compartments (S).

As per the Scientific Forest Management Guidelines (2071), 15 to 25 shelter/mother trees per hectare are retained after seeding felling (DoF, 2014). The shelter trees will be removed 10 years after seeding felling, assuming regeneration has been successfully established. The condition of the annual felling plot is the fundamental basis of the prioritization of regeneration felling. This means that plots with a high number of mature trees but low regeneration density are harvested first. Due to the urgency of restoring these plots, forest managers focus on the regeneration of these degraded plots with low presence of seedlings or saplings prior to felling. A fence was placed around all harvested (seeding felling) plots to protect the regeneration from browsing.

Data collection

This study adopted a systematic sampling design to establish sample plots in the field. In each annual felling plot, three sample plots of 10 m² were established, arranged at the vertices of an isosceles triangle (Figure 2). The sample plots were rectangular shape (5m × 2m). Although circular plots are widely used, they are found to have systematic errors because of the radial distribution of lines (Yue et al., 2023). Therefore, we used rectangular plots for the data collection. The first plot was selected 30 m west from the southeastern

corner and then 30 m north from the edge towards the interior of the felling plot. Various distances, ranging from 20 to 100 m from the edge into the forest interior, have been utilized to minimize the edge effect on regeneration in tropical forests (Benítez-Malvido et al., 2018).

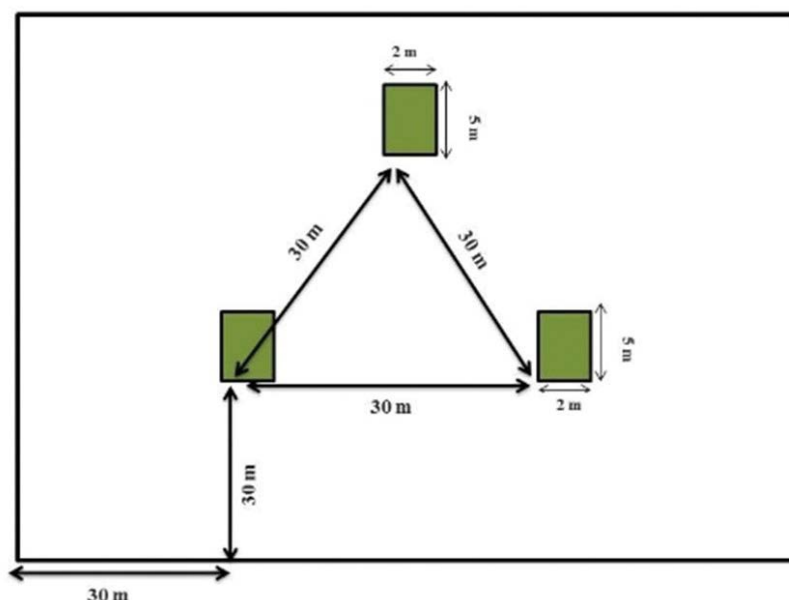


Figure 2. Layout of inventory plot indicating plot dimensions and inter-plot distances used for Sampling Design

Following these facts, and practice of existing study, we determined 30 m distance between edge to interior (Hladnik et al., 2020). The second plot was fixed 30 m perpendicular to the first and the third was 30 m away at 45-degree northwest from the first plot. This was adopted as a cluster sampling approach, with three rectangular plots in each cluster (Tokola & Shrestha, 1999). The north-south sides of the sample plot were slightly longer (5 m) whereas the east-west sides were shorter (2 m) in these plots. The researchers measured 270 sample plots in 90 clusters, by counting and recording seedlings and samplings of every species within each sample plot. The forest inventory was conducted in April 2023.

For this study, a seedling is a young plant developing from the seed, with a height of less than 1.3 m; and a sapling is a young plant with a height greater than 1.3 m and dbh less than 5 cm (CPFD, 2004). In this study, both seedlings and saplings are commonly called as regeneration (FRTC, 2022). This study counted seedlings by species, and measured dbh and height of all saplings. In addition, canopy density was also recorded in the centre of each sample plot using a Spherical Crown Densiometer, Convex Model A. This study also used secondary data from the Divisional Forest Office, Kapilvastu, Nepal particularly of trees at canopy layer, before regeneration felling in each annual felling area.

Data analysis

Regeneration plots were divided into three groups based on age, determined by the number of years since regeneration/seeding felling, with intervals of three years, as a good seed year for Sal occurs every three years (Champion & Seth, 1968). The age of the plot is measured by the number of years since the regeneration/seeding felling. These groups are: Age1 with age one to three years old plots, Age2 with age four to six years old plots, and Age3 with age seven to nine years old plots. Different indices (i.e., Shannon Diversity Index, Dominance index, Jaccard Similarity Index, and Pielou's index) were used to measure the diversity of seedling, sapling, and regeneration layers. The diversity in the community is quantified by the Shannon Diversity Index (Shannon, 1948). This is expressed as:

$$H = \sum_{i=1}^n P^i \times \ln(P^i) \quad (i)$$

Where, H is Shannon Diversity Index, P_i is proportion of individuals belong to i th species, and n is the number of species in the study area. Higher H value means higher diversity, which varies from 0 to 1.

This study calculated the Simpson's dominance index to analyse the dominance of one or few species within the study area. It was concluded that greater value meant higher dominance of one or few species. This is negatively correlated with diversity. This is expressed as:

$$D = \sum_{i=1}^S p_i^2 \quad (\text{ii})$$

Where, D denotes Simpson's dominance index, P_i is the proportion of the i th species and S is the total number of species. The index ranges from 0 to 1. The dominance index of 0.50 means no species dominance, 0.50-0.75 means moderate dominance, while 0.75-1 means high dominance (Odum & Barrett, 1971).

Jaccard similarity index was computed to evaluate the proportion of species of total species shared by two or more strata (Bag et al., 2019). Here, strata are different layers, such as canopy and seedlings; canopy and saplings; seedlings and saplings; and canopy and regeneration. This is expressed as:

$$S_j = \frac{a}{(a+b+c)} \quad (\text{iii})$$

Where,

S_j is Jaccard Similarity coefficient, "a" is the number of common species in two layers, "b" is the number of unique species in the first layer, and "c" is the number of unique species in the second layer. S_j in different layers helps to understand species dynamics (Ivchenko & Honov, 1998).

Pielou's index was computed to assess how evenly species are distributed in the community (Pielou, 1966). It is calculated as:

$$J = \frac{H'}{\ln(S)} \quad (\text{iv})$$

Where, J represents Pielou's evenness index, H' is the Shannon-Wiener index, and $\ln(S)$ is the natural logarithm of species richness. It ranges from 0 to 1. 1 means perfectly even distribution (all species are equally abundant), less than 1 means uneven distribution (some species dominate), and 0 means only one species present.

A normality test was performed to check if the data follows a normal distribution, which is an assumption for many statistical analyses. It helps determine whether to use parametric tests or switch to non-parametric methods based on the distribution of the data. The Jarque Bera tests were carried out for all variables by age group (Glinskiy et al., 2024). The results indicate that the datasets were not normally distributed. Therefore, Kruskal-Wallis test, the non-parametric equivalent of a one-way analysis of variance, was conducted to compare means of age groups to determine if there are statistically significant differences among them (McKight & Najab, 2010). This test does not answer which pairs are differed significantly, therefore, a post-hoc test is required. The Dunn test, an appropriate non-parametric method for pairwise comparisons, was performed (Dinno, 2015). Only significant variables were considered for the Dunn test.

Results

Descriptive statistics

Table 1 reports the descriptive statistics of the plots. The results showed the seedling layer had the highest H and species richness and the sapling layer had the lowest. But D was the highest at the sapling layer and lowest at the seedling layer. Among the overall population at the regeneration layer, 72% of the total individuals were seedlings. Similarly, 85% of overall individuals at the regeneration layer were light demanding species. Of the total individuals, less than 1% of the sapling layer and almost 17% of the seedling layer were shade-tolerant species.

The results also showed that canopy cover increases with age. Canopy cover of Age3 (69%) was consistently higher than Age2 (56%) and Age1 (45%).

Table 1. Diversity and dominance indices, species richness and density (standard deviation in parentheses) in Sal forests of Kapilvastu, Nepal.

Variables	Regeneration	Sapling	Seedling
Diversity index	0.82 (0.52)	0.24 (0.34)	0.80 (0.49)
Regeneration species richness (Number)	3.69 (1.75)	1.38 (0.98)	3.15 (1.49)
Dominance index	0.57 (0.25)	0.67 (0.37)	0.55 (0.25)
Total density (Number/ha)	16,427 (11,304)	3,017 (2,904)	13,433 (7,562)
Light-demanding density (Number/ha)	13,952 (10,606)	2,789 (2,654)	11,186 (7,043)
Shade-tolerant density (Number/ha)	2,475 (2,842)	228 (737)	2,247 (2,793)

Plant species at regeneration layer

We recorded 35 species in the seedling layer; 19 were light demanding species, five were shade-tolerant species and one was intermediate shade-tolerant species (Table 2). The light tolerance (the ability to survive, grow, and reproduce under specific light conditions) of the remaining species, primarily shrubs and bushes, was not identified due to a lack of available information. In the sapling layer, 11 species were light-demanding, and four were shade-tolerant, while the remaining four species were unspecified. Sal is the dominant species in both layers.

Table 2. Density of species (Number/ha) by their ecological characteristics and age in Sal Forests of Kapilvastu, Nepal.

Layer	Species	Character	Age1	Age2	Age3
Seedling	<i>Acacia Catechu</i>	LD ¹	0	22	79
	<i>Achyranthes bidentta</i>	IshT ²	0	56	11
	<i>Anogeissus latifolia</i>	LD	12	22	45
	<i>Aegle marmelos</i>	LD	48	189	180
	<i>Bauhinia racemosa</i>	LD	36	44	90
	<i>Buchanania latifolia</i>	LD	36	22	79
	<i>Careya arborea</i>	LD	60	67	11
	<i>Cassia fistula</i>	LD	0	32	34
	<i>Dalbergia latifolia</i>	LD	0	11	11
	<i>Diospyrus tomentosa</i>	LD	167	44	236
	<i>Garuga pinnata</i>	LD	0	11	22
	<i>Hedychium spicatum</i>	ShT ³	623	622	1,607
	<i>Madhuca latifolia</i>	LD	0	11	22
	<i>Mallotus philippensis</i>	ShT	500	411	989
	<i>Phyllanthus emblica</i>	LD	12	22	45
	<i>Pterocarpus marsupium</i>	LD	12	111	34
	<i>Schleichera oleosa</i>	ShT	286	422	270
	<i>Semicarpus anacardium</i>	ShT	0	11	34
	<i>Shorea robusta</i>	LD	7,381	7,722	7,422
	<i>Syzygium cumini</i>	ShT	0	11	0
	<i>Terminalia alata</i>	LD	631	211	213
	<i>Terminalia bellirica</i>	LD	24	22	45
	<i>Terminalia chebula</i>	LD	60	144	270

Layer	Species	Character	Age1	Age2	Age3
Sapling	<i>Aegle marmelos</i>	LD	0	60	90
	<i>Careya arborea</i>	LD	0	30	0
	<i>Cassia fistula</i>	LD	30	60	0
	<i>D. latifolia</i>	LD	0	30	30
	<i>Madhuca latifolia</i>	LD	0	60	0
	<i>M. philippensis</i>	ShT	0	120	60
	<i>Schleichera oleosa</i>	ShT	90	60	30
	<i>Semecarpus anacardium</i>	ShT	30	0	0
	<i>S. robusta</i>	LD	6,990	8,670	4,200
	<i>S. cumini</i>	ShT	0	90	150
	<i>Terminalia alata</i>	LD	1,050	450	390
	<i>T. bellirica</i>	LD	0	30	0
	<i>T. chebula</i>	LD	60	150	90
	<i>T. grandis</i>	LD	30	0	0
	<i>Trema orientalis</i>	LD	0	30	0

¹LD= Light Demanding species

²IshT= Intermediate Shade Tolerant

³ShT= Shade Tolerant

Of the total 270 plots, seven plots (one of Age1 and six of Age3 groups) did not have regeneration. Among the remaining plots contained regeneration; Age1, Age2 and Age3 had 89, 90 and 84 plots, respectively. Table 3 reports the density of light-demanding and shade-tolerant species. Light demanding species dominated all layers and age groups. The ratio of light-demanding to shade-tolerant species was higher in the younger age group (Age1) compared to the older group (Age2 and Age3). Light-demanding species dominated significantly more in the sapling layer than in the seedling layer across all age groups. The results also showed that density of shade-tolerant species decreased with age in all layers.

Table 3. Mean density of species (Number per ha) at different layers by light demanding nature and age (Standard Error in parentheses) in Sal forests of Kapilvastu, Nepal.

Variable	Age1	Age2	Age3
LD regeneration	15,033 (8,854)	14,622 (10,113)	13,341 (6,968)
ShT regeneration	3,224 (3,563)	2,211(2,285)	1,964 (2,346)
LD sapling	1,652 (1,432)	3,545 (2,509)	3,187 (2,378)
ShT sapling	269 (938)	266 (632)	142 (583)
LD seedling	9,808 (7,904)	11,078 (7,448)	10,155 (7,601)
ShT seedling	2,955 (3,544)	1,944 (2,245)	1,821 (2,255)

Note: LD = Light demander, ShT = Shade Tolerant

Of the total 270 plots, 77 (29%) plots did not have common species in seedling and sapling layers. This meant all species present in seedling layer and sapling layer were identical in these plots. A few species were common in both seedling and sapling layers. Most of the plots (59%) had one common species, followed by two (10%) and three (0.74%). Overall average S was 0.28 with standard deviation 0.32. By age group, Age1, Age2, and Age3 groups had an average number of common species of 1.08, 0.85 and 0.59, respectively. Similarly, S was 0.34, 0.37, and 0.24 in Age1, Age2 and Age3 respectively. The indices between the age groups were not significantly different.

Variations in regeneration

The results suggest that regeneration *H* and regeneration density decreased with age (Table 4). But *D* was higher in the older plots. Species richness at the regeneration layer was highest in Age2 group and lowest in Age3 group. *J* was the highest in Age1 and lowest in Age2. At the sapling layer, species richness and *D* increased with age. But *H*, *J* and density were not straightforward. *H*, *J* and density were the highest in Age2 and the lowest in Age1 group. At the seedling layer, *H*, species richness and density decreased with age. But, *J* was the highest in Age1 and the lowest in Age2 group. The results also suggested that *D* was consistently higher in the sapling layer as compared to the seedling layer. But other variables were consistently higher in the seedling layer.

Table 4. Diversity index, evenness index, species richness, dominance index, density at regeneration, seedling and sapling layers across age groups (standard deviation in parentheses) in Sal forests of Kapilvastu, Nepal.

Variables	Age1	Age2	Age3
Diversity index regeneration	0.88 (0.51)	0.81 (0.56)	0.76 (0.48)
Species Richness regeneration (Number)	3.76 (1.73)	3.95 (1.99)	3.34 (1.41)
Evenness index regeneration	0.61 (0.32)	0.52 (0.31)	0.58(0.30)
Dominance index regeneration	0.53 (0.24)	0.59 (0.26)	0.59 (0.25)
Density regeneration (Number/ha)	17,145 (11,302)	16,833 (9,951)	15,305 (9,813)
Diversity index sapling	0.12 (0.28)	0.33 (0.38)	0.26 (0.33)
Species Richness sapling (Number)	0.94 (0.81)	1.7 (1.16)	1.51 (0.76)
Evenness index sapling	0.14(0.32)	0.35(0.35)	0.34 (0.40)
Dominance index sapling	0.62 (0.44)	0.63 (0.35)	0.77 (0.28)
Density sapling (Number/ha)	1,921 (2,133)	3,811 (3,577)	3,329 (2,451)
Diversity index seedling	0.90 (0.48)	0.77 (0.51)	0.72 (0.48)
Species Richness seedling (Number)	3.53 (1.55)	3.1 (1.55)	2.79 (1.26)
Evenness index seedling	0.70 (0.28)	0.62 (0.33)	0.64 (0.34_
Dominance index seedling	0.51 (0.23)	0.56 (0.26)	0.58 (0.25)
Density seedling (Number/ha)	15,224 (9,169)	13,022 (6,374)	11,976 (6,484)

The results of the Kruskal-Wallis test indicated no significant differences in all tested variables (*H*, species richness, *J*, and *D*) among the age groups in the regeneration layer (Table 5). However, these variables showed significant differences in the sapling layer, and only species richness was significantly different in the seedling layer.

Table 5. Results of Kruskal-Wallis test for Diversity Index, Species Richness, Evenness Index, and Dominance Index across Age groups at Regeneration, Seedling and Sapling layers in Sal forests of Kapilvastu, Nepal.

Variables	Rank Sum			χ^2	P-value
	Age1	Age2	Age3		
Diversity index regeneration	12,633	11,630	10,452	2.471	0.29
Species richness regeneration	12,040	12,703	9,972	4.02	0.13
Evenness index regeneration	12,812	10,688	11,216	4.96	0.08
Dominance index regeneration	10,746	12,454	11,515	2.95	0.22
Diversity sapling	9,243	13,699	11,773	19.51	0.00

Variables	Rank Sum			χ^2	P-value
	Age1	Age2	Age3		
Species richness sapling	8,687	13,758	12,271	27.84	0.00
Evenness index sapling	9,243	13,299	12,174	23.23	0.00
Dominance index sapling	11,759	10,620	12,301	6.08	0.04
Diversity seedling	13,067	11,529	10,120	5.54	0.06
Evenness index seedling	12,222	11,383	11,110	0.91	0.63
Species richness seedling	13,344	11,641	9,730	8.85	0.01
Dominance index seedling	10,669	12,146	11,900	3.75	0.15

Table 6 reports the results of the Dunn test of those significant variables in Table 5. *H*, species richness and *J* in the sapling layer were significantly different in two pairs: Age1-Age2 and Age1-Age3. But *D* was only in Age2-Age3 pair. In the case of species richness in the seedling layer, only Age1-Age3 pair was significantly different.

Table 6. Results of Dunn's Post-Hoc Test for Pairwise Comparisons of Variables Found Significant in the Kruskal-Wallis Test (Table 5).

Variables	Age1-Age2	Age1-Age3	Age2-Age3
Diversity sapling	-4.76***	-3.51***	1.17
Species richness sapling	-5.13***	-4.43***	0.62
Evenness index sapling	-4.33***	-3.98***	0.27
Dominance index sapling	1.32*	-1.25	-2.56***
Species richness Seedling	-1.32*	-1.88**	-0.58

Note: *, **, and *** denote significant at 10%, 5%, and 1%.

Discussion

The results of this study suggest that regeneration species richness in *S. robusta* forests increases over time after regeneration felling. This can be translated from the higher species richness and diversity index in the seedling layer compared to the sapling layer. Gap created by the regeneration felling encourages light-exposed growing environments (Hammond & Pokorný, 2020). This means light demanding species colonized the gap first, as they can perform photosynthesis at high rates, thus producing more seedlings (Kitajima, 1994; Kozłowski & Pallardy, 1997; Velázquez & Wiegand, 2020). The dominance of light demanding species in the seedling layer (83%) and sapling layer (92%) supports this statement indicating that their prevalence diminishes in the lower canopy layers. Usually, shade-tolerant species exhibit high recruitment under the selection system, whereas light-demanding species thrive in the irregular shelterwood system (Klopčic & Boncina, 2012).

Dominance of the light demanding species under conditions of canopy opening can be expected even under natural disturbances. The existing empirical studies show that *S. robusta* accounts for only one-fourth of the total regeneration density under the canopy, but its proportion rises significantly to 73% in gap areas (Sharma et al., 2019; Pokhrel et al., 2024). This proportion remains the same at different age groups of the regeneration plots. The dominance of light-demanding species follows a similar pattern across all age groups in the regeneration plots until the first thinning. This trend is also observed in a study by Awasthi et al., (2019), which measured the same plots at four-year intervals, in 2014 and 2018. The composition of light demanding species in the sapling layer resembles the canopy structure of Sal forests in Nepal. Usually, canopy of Sal Forest is dominated by *S. robusta* and *Terminalia alata* Heyne ex Roth; and occasionally by other *Terminalia* spp (Timilsina et al., 2007). They have recorded that Sal forests have different clusters based on the associated species with *S. robusta* such as *Buchanania*

latifolia Roxb., *Terminalia alata* Heyne ex Roth, and *Cleistanthus operculatus* (Roxb.) Merr. & L.M. Perry. Once regenerations grow and provide shade, they create a micro-environment in their surroundings. The environment with gradual closing of gaps favours regeneration of shade-tolerant species (Yamamoto, 2000). Shade-tolerant species like *Mallotus philippensis* (Lam.) Müll. Arg., *Schleichera oleosa* (Lour.) Merr., *Syzgium cumini* (L.) Skeels, and *Semecarpus anacardium* L.f. are commonly appeared shade-tolerant species in Sal Forest (Tiwari & Shukla, 1995; Sapkota et al., 2021). These species regenerate successfully under a less intense irregular shelterwood system, while intermediate-tolerant species are more frequently found across all shelterwood system variants (Raymond et al., 2009). Furthermore, the moderate dominance, with a dominance index ranging from 0.55 to 0.67, reflects the presence of a diverse array of species. The study also reveals that forest users do not perceive any local extinction of species resulting from regeneration felling under the shelterwood system in Nepal (Bhusal et al., 2020). Shelterwood system manages competition expansion, which ensures that the desired tree species have enough resources to regenerate successfully (Raymond et al., 2009).

The results also indicated that regeneration felling under the shelterwood system fosters a favourable environment for regeneration. The regeneration density (16,427/ha) is nearly four times higher than the initial density of seedlings (2,877/ha) and saplings (2,080/ha) before regeneration or seeding felling (Tilaurakot CFM, 2011). The density of individuals in the regeneration layer of Sal forests under the irregular shelterwood system is recorded to range from 10,000 to 20,000 per hectare (Awasthi et al., 2020; Belbase et al., 2022; Pokhrel et al., 2024). These studies have also shown that the sapling layer has a lower number of species compared to the seedling layer. But the proportion varies with locations from 7 to 25 percent (Awasthi et al., 2020; Pokhrel et al., 2024). The sapling density in the study area falls within this range. The findings indicate an inverse relationship between seedling and sapling densities, where higher density in the seedling layer corresponds to lower density in the sapling layer.

The results indicated that younger plots exhibit greater species richness, diversity index, and density in regeneration. However, older age groups show a higher dominance index. This could be attributed to the practice of prioritizing regeneration felling in degraded plots. Older plots may have lacked sufficient advanced growth prior to regeneration felling, whereas plots subjected to regeneration felling at a later stage were in better condition with more advanced growth. This likely explains why younger plots possess a more robust regeneration layer. In Sal forests, advanced growth plays a significant role in sustaining the regeneration layer. Their presence may affect regeneration layer in terms of density and plant species richness (Rautiainen & Suoheimo, 1997). Therefore, the study area could not illustrate a clear trend in the variables related to regeneration.

Conclusions

Canopy opening under shelterwood system after regeneration felling provides a favourable environment for light demanding species at first. The number of light demanding species is five times higher than that of shade-tolerant species. The dominance of light-demanding species in the early stage after seeding felling is expected. However, this does not imply that the shelterwood system leads to the development of monospecific forests and reduce species richness. This is because when regeneration grows and new forest layers develop, they create a favourable environment for other species over time. Usually, light demanding species dominate the upper canopy with a high dominance index. In sapling layer, low species richness and higher dominance index illustrate this situation.

Since, the quantity of growing stock varies across plots, the results do not establish a clear trend over time. This variability may be influenced by the presence of advanced growth. Therefore, it is suggested to establish experimental plots by excluding advanced growth to evaluate the trend in the regeneration layer's trend over time. The location, size, and density of retention trees can significantly impact regeneration by modifying light conditions, while soil conditions also play a crucial role in Sal regeneration. However, these factors were not considered in this study. Future research should incorporate these variables to generate more robust findings and inform policy for determining the optimal number of shelter trees. Furthermore, we propose to record advanced growth prior to regeneration felling. This approach will provide a clearer understanding of regeneration dynamics in Sal forests and support more effective management strategies.

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