

Report on

**Assessing Forest Growth under different Silvicultural
Systems in Madesh Province, Nepal**



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Forest Research and Training Centre
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Executive Summary

Background

Terai Forests are considered as a highly productive forests, as it is dominated by high value timber species such as Sal (*Shorea robusta*). The main objective of terai forest management is timber production followed by fuelwood and small-timber. Therefore, understanding tree growth is an important aspect to optimize benefits from forest management. There are two silvicultural systems in practice in Nepal. These include: shelterwood and selective cutting understood as selection system. In this context, this study, conducted in Madesh Province, Nepal, aimed to assess diameter growth under different silvicultural systems to inform evidence-based forest management strategies.

The primary objective was to evaluate forest growth under different silvicultural systems in Madesh Province. The specific objectives are:

- Estimating the diameter growth rate (DBH) of trees over time.
- Assessing differences in tree growth between shelterwood and selection silvicultural systems.

Methods

The study was conducted in Bara and Rautahat districts, covering five forest units: Hatemalo Community Forest, Janaekata Community Forest, Janajyoti Community Forest, Janasrijanshil Community Forest, and Gadimai Collaborative Forest. These sites were selected due to the availability of data and practices of silvicultural systems. Data were collected from 2,432 trees with DBH $\geq$ 20 cm, measured at two time points (5–8 years apart). Key steps included:

- Data Collection: DBH was measured at 1.3 meters using diameter tapes, with trees permanently marked for consistency.
- Growth Calculation: Annual Diameter Growth Rate (AGR) was calculated as $(DBH_2 - DBH_1) / \text{time span}$.
- Baseline data were taken from the respective Division Forest Offices and Forest User Groups.
- Statistical Analysis: Linear Mixed-Effect Models (LMM) were used to analyze AGR, with fixed effects (management regime, silvicultural system, species, diameter class) and random effects (site variability). ANOVA and Tukey's HSD tests were employed for post-hoc analysis.



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Key Findings

- **Silvicultural Systems:** Shelterwood systems significantly outperformed selection systems, with higher AGR ($p < 0.001$). This suggests reduced competition in shelterwood systems enhances growth.
- **Tree Species:** Sal (*Shorea robusta*) exhibited the highest AGR (0.93 cm/year), while Asna (*Terminalia tomentosa*) exhibited the least (0.63 cm/year), highlighting species-specific growth patterns.
- **Site Variability:** Growth rates varied across sites, with Janaekata Community Forest showing the highest AGR for Sal (1.43 cm/year). Site conditions (e.g., soil, microclimate) played a critical role.
- **Diameter Class:** Middle diameter classes (30–70 cm) showed slightly higher growth, but the trend was not statistically significant, indicating stable growth across most size classes.
- **Management Regime:** Collaborative Forest Management (CFM) had marginally higher AGR than Community Forests (CF), but the difference was not significant ($p = 0.576$).

Conclusions and Recommendations

The findings underscore the importance of silvicultural systems and species selection in forest management. Shelterwood systems, by reducing competition, create favorable conditions for faster growth, particularly for light-demanding species like Sal. Site-specific factors, such as ecological conditions and management practices, further influence growth rates. The dominance of Sal in growth performance aligns with its ecological adaptability and economic value. The minimal impact of diameter class suggests that growth is more influenced by external factors (e.g., silviculture) than tree size alone. The key recommendations are;

- **Adopt Shelterwood Systems:** Prioritize shelterwood systems in Sal-dominated forests to maximize growth and productivity.
- **Species-Specific Management:** Tailor silvicultural practices to species requirements, favoring Sal in high-productivity sites.
- **Exploitable size:** Determine 70 cm dbh as an exploitable size of Sal tree as growth rate slows down beyond this size,
- **Site-Adaptive Strategies:** Conduct localized assessments to account for site variability and optimize management interventions.



ESTR

सारांश

पृष्ठभूमि

तराईका वनहरूलाई अत्यन्त उत्पादनशील वनको रूपमा लिइन्छ किनकि यहाँ साल (*Shorea robusta*) जस्ता मूल्यवान काठ प्रजातिहरूको बाहुल्यता रहेको छ । तराई वन व्यवस्थापनको मुख्य उद्देश्य काठ उत्पादन हो र त्यसपछि दाउरा र साना काठको उत्पादन हो । तसर्थ, वन व्यवस्थापनबाट लाभ लिनका लागि रूखहरूको वृद्धिलाई बढ्नु महत्त्वपूर्ण पक्ष हो । नेपालमा दुइवटा वन सम्बर्द्धन प्रणाली (सिल्विकल्चरल सिस्टम) प्रचलनमा छ । यीनिहरू हुन: छहारी रूख प्रणाली (सेल्टरवुड सिस्टम) र छनौट कटान जसलाई सेलेक्सन सिस्टम को रूपमा बुझिन्छ । यसै सन्दर्भमा नेपालको मधेश प्रदेशमा गरिएको यस अध्ययनले अनुसन्धान र प्रमाणमा आधारित वन व्यवस्थापन रणनीतिलाई टेवा पुर्याउन विभिन्न वन सम्बर्द्धन प्रणालीमा आधारित वनमा रूखहरूको व्यास वृद्धिको अध्ययन गर्ने उद्देश्य लिएको थियो । यस अध्ययनको प्राथमिक उद्देश्य मधेश प्रदेशमा विभिन्न वन सम्बर्द्धन प्रणालीमा आधारित वनको वृद्धिको मूल्याङ्कन गर्नु थियो । खास उद्देश्यहरू निम्न छन्:

- विभिन्न समय अन्तरालमा रूखहरूको व्यास (DBH) वृद्धि दर यकिन गर्ने ।
- छहारी रूख प्रणाली (सेल्टरवुड सिस्टम) र छनौट कटान/ सेलेक्सन सिस्टम मा आधारित वनका रूखहरू विचको वृद्धिमा भिन्नता मूल्याङ्कन गर्ने ।

अध्ययन विधि

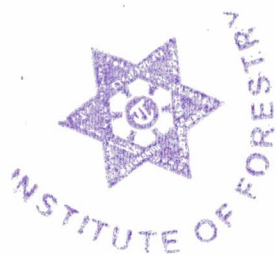
यो अध्ययन बारा र रौतहट जिल्लाका वन सम्बर्द्धन प्रणालीमा आधारित वन व्यवस्थापन गरिएका वनहरू: हातेमालो सामुदायिक वन, जनएकता सामुदायिक वन, जनज्योति सामुदायिक वन, जनश्रीजनशील सामुदायिक वन र गढिमाई साझेदारी वन गरी पाँचवटा वन क्षेत्रलाई समेटेर अध्ययन गरिएको थियो । यी क्षेत्रहरूमा वन सम्बर्द्धन प्रणालीमा वन व्यवस्थापन भएको र जानकारी समेत उपलब्ध हुने भएकोले यी वन इकाईहरू छनौट गरिएको हो । २० सेन्टिमिटर र सो भन्दा बढी व्यास (DBH) भएका २,४३२ रूखहरूको दुई



STRV

- Long-Term Monitoring: Establish continuous monitoring to track growth responses to silvicultural practices and climate change.
- Community Engagement: Strengthen collaboration with local communities to ensure sustainable implementation of management practices.

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(०.६३ सेन्टिमिटर/वर्ष) एजीआर रह्यो। यो तथ्याङ्कले प्रजाति अनुसार फरक वृद्धि ढाँचालाई महत्व दिन्छ ।

- क्षेत्रगत विविधता: वृद्धिदर क्षेत्र अनुसार फरक पाईयो। जनएकता सामुदायिक वनमा साल को उच्चतम उच्च वार्षिक वृद्धि दर (१.४३ सेन्टिमिटर/वर्ष) पाईयो। क्षेत्रको अवस्था (उदाहरणका लागि माटो, स्थानिय जलवायु) ले वृद्धिदरमा महत्वपूर्ण भूमिका खेलेको देखिन्छ ।
- व्यास वर्ग: मध्यम व्यास वर्गमा (30-70 सेमी) अलिकति उच्च वृद्धि देखायो, तर यो वृद्धिदर statistically significant थिएन। यसले अधिकांश व्यासको आकार वर्गहरूमा स्थिर वृद्धि भएको संकेत गर्दछ ।
- वन व्यवस्थापन प्रणाली: साझेदारी वनमा (CFM) सामुदायिक वन (CF) भन्दा थोरै बढी उच्च वार्षिक वृद्धि दर AGR थियो, तर यो फरक statistically significant ($p = 0.576$) थिएन ।

निष्कर्ष र सिफारिसहरू

यस अध्ययनका नतिजाहरूले वन व्यवस्थापनमा वन सम्बर्दन प्रणाली र प्रजाति चयनको महत्वलाई उजागर गरेको छ । छहारी रूख प्रणालीले प्रतिस्पर्धा कम गरेर, द्रुत वृद्धिको लागि अनुकूल परिस्थिति सिर्जना गर्दछ, विशेष गरी बढि प्रकाश चाहिने साल जस्ता प्रजातिहरूको लागि । क्षेत्रगत-विशिष्ट कारकहरू जस्तै पारिस्थितिक अवस्था र व्यवस्थापन अभ्यासहरूले वृद्धि दरलाई थप प्रभाव पार्दछ । वृद्धि दरमा सालको प्रभुत्व र यसको पारिस्थितिक अनुकूलन क्षमता र आर्थिक महत्वसँग मेल खाएको देखिन्छ । व्यास वर्गको न्यूनतम प्रभावले के जनाउँछ भने रूखहरूको वृद्धि तिनका आकार वर्गले मात्र भन्दा बाह्य कारकहरूले (जस्तै, सिल्विकल्चर) बढी प्रभावित गर्दछ ।

यस अध्ययनको आधारमा मुख्य सिफारिशहरू निम्न अनुसार छन् ।

- छहारी रूख प्रणाली अवलम्बन गर्ने: वृद्धि र उत्पादकत्व बढाउनको लागि सालको बाहुल्यता भएका वनहरूमा छहारी रूख प्रणालीलाई प्राथमिकता दिने ।



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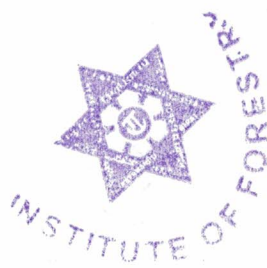
समयमा (५-८ वर्षको अन्तरालमा) मापन गरी तथ्याङ्क संकलन गरिएको थियो । तथ्याङ्क संकलनका लागि गरिएका मुख्य चरणहरू यस प्रकार छन् ।

- तथ्याङ्क संकलन: DBH टेपले जमिनको सतहबाट रुखहरूको 1.3 मिटर उचाईमा व्यास मापन गरिएको थियो र मापन भएका रुखहरूमा स्थायी रूपमा चिन्ह लगाइएको थियो जसले गर्दा प्रत्येक पटक नाप्दा स्थिरता कायम गर्न सकियोस ।
- वृद्धि गणना: छातिको उचाईमा व्यास (DBH) को वार्षिक वृद्धि दर (AGR) पत्ता लगाउन $(DBH_2 - DBH_1) / \text{Time span}$ को सूत्र प्रयोग गरिएको थियो । यसमा, DBH_2 ले हाल मापन गरिएको व्यास, DBH_1 ले संवर्दन कार्य अन्तर्गत कटान गरिएको समयमा मापन गरिएको व्यास, र Time span ले समय अन्तराल (वर्ष) लाई जनाउँदछ ।
- सम्बन्धित डिभिजन वन कार्यालय र वन उपभोक्ता समूहबाट आधारभूत तथ्याङ्क लिइएको ।
- तथ्याङ्क विश्लेषण: Linear Mixed-Effects Model (LMM) प्रयोग गरी छातिको उचाईमा व्यासको वार्षिक वृद्धि दर (AGR) विश्लेषण गर्न स्थिर प्रभावका रूपमा वन व्यवस्थापन प्रणाली, वन संवर्दन प्रणाली, प्रजाति, व्यास वर्ग र अनियमित प्रभावका रूपमा वनको क्षेत्रगत विविधतालाई प्रयोग गरिएको थियो । पोस्ट-हक विश्लेषण ANOVA and Tukey's HSD परीक्षण बाट गरिएको थियो ।

मुख्य परिणामहरू

- वन संवर्दन प्रणाली: छहारी रुख प्रणालीमा सेलेक्सन प्रणाली भन्दा उच्च वार्षिक वृद्धि दर ($p < 0.001$) पाईएको छ । यसको अर्थ यो हो कि छहारी रुख प्रणालीमा रुखहरू बीच प्रतिस्पर्धा कम हुनुले वृद्धिलाई बढावा दिएको देखिन्छ ।
- रुख प्रजातिहरू: साल (*Shorea robusta*) को सबैभन्दा बढी उच्च वार्षिक वृद्धि दर (०.९३ सेन्टिमिटर/वर्ष) रहेको पाईयो जबकि साज वा असना (*Terminalia tomentosa*) को सबैभन्दा कम

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- प्रजाति-विशिष्ट व्यवस्थापन: प्रजातिहरूका आवश्यकता अनुसारका वन सम्बर्दनका अभ्यासहरू लागु गर्ने, उच्च उत्पादकत्व भएका क्षेत्रहरूमा साललाई प्राथमिकता दिने ।
- कटान गर्न सकिने आकार: ७० सेन्टिमिटर DBH लाई साल प्रजातिको कटान गर्ने आकार निर्धारण गर्ने किनकि यस पछि सालको वृद्धिदर कम हुन्छ ।
- क्षेत्र-अनुकूल रणनीतिहरू: क्षेत्रगत विविधता अनुसार अधिकतम सदुपयोग गर्नका लागि स्थानीयकृत मूल्याङ्कनहरू सञ्चालन गर्ने ।
- दीर्घकालीन अनुगमन: वृद्धिदरमा वन सम्बर्दनका अभ्यासहरू र जलवायु परिवर्तनको प्रभाव मूल्याङ्कनका लागि दीर्घकालीन अनुगमन प्रणालिको स्थापना गर्ने ।
- समुदायको सहभागिता: वन व्यवस्थापन अभ्यासहरूको दिगो कार्यान्वयन सुनिश्चित गर्न स्थानीय समुदायहरूको सहभागिता र सहकार्य सुदृढ गर्ने ।



Acronyms

AGR	Annual Growth Rate
AIC	Akaike Information Criterion
ANOVA	Analysis of Variance
CF	Community Forest
CFM	Collaborative Forest Management
CV	Coefficient of Variation
DBH	Diameter at Breast Height
DFO	Division Forest Office
DGP	Diameter Growth Percentage
FRTC	Forest Research and Training Centre
HSD	Tukey's Honest Significant Difference test.
IQR	Interquartile Range
LMM	Linear Mixed Effects Model
LOESS	Locally Estimated Scatterplot Smoothing
SD	Standard Deviation
SFM	Sustainable Forest Management



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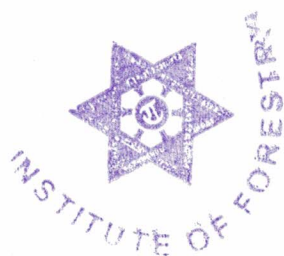
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1. Introduction

Forest ecosystems in Nepal are highly diverse and serve as vital sources of biodiversity conservation, livelihood support, and ecosystem services. These forests are a primary source of timber, fuelwood, non-timber forest products, and other essential goods and services that sustain rural communities. In the Terai region, *Shorea robusta* (Sal) forests represent one of the most ecologically and economically significant resources, contributing notably to timber production and supporting local livelihoods (Pokhrel *et al.*, 2024). To enhance the productivity and sustainability of these forests, the Government of Nepal has adopted a sustainable forest management (SFM) approach that emphasizes the application of appropriate silvicultural systems. While the effects of silvicultural intervention; particularly reduction in competition on tree growth have been extensively studied in even-aged stands, their impacts on retained cohorts in uneven-aged forests remain less understood (Biging & Dobbertin, 1995).

Among individual tree attributes, tree diameter growth, typically measured as diameter at breast height (DBH), serves as a fundamental indicator of forest health, productivity, and biomass accumulation (Zhang *et al.*, 2012). Forest management requires information on growth pattern for individual trees species to assess forest stand productivity, as measuring accurately total or merchantable tree height is difficult, DBH has become the most important variable for allometric equations (da Silva *et al.*, 2002). DBH is not only easy to measure but also closely correlated with other important tree characteristics such as height and volume, making it a critical metric in forest inventory and management (Zhang *et al.*, 2004). Moreover, the distribution of trees by DBH class provides insights into stand structure, forest dynamics, and potential yield. Tree growth, particularly in diameter, is strongly influenced by the silvicultural system employed. These systems; whether shelterwood or selection system; alter forest structure by affecting light availability, competitive interactions, and regeneration patterns (Bianchi *et al.*, 2023). Selection system is a type of silvicultural system practiced in full-storied forests, stands having no clear development phase (like regeneration or thinning) and maintains a similar structure over time, logging is through single-tree selection, occurring on a regular or a non-regular basis (Ekholm *et al.*, 2022). In shelterwood system, trees are removed in a series of cuts and new stand is achieved under the shelter of remaining trees called shelterwood or mother trees. Shelterwood systems provide greater sunlight, favoring fast-growing and light-demanding species,



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while selection systems maintain continuous canopy cover, benefiting shade-tolerant species (Pokhrel *et al.*, 2024).

Previous studies have demonstrated that tree growth responses under different silvicultural systems are influenced by both stand and tree level factors. Disturbance intensity and spatial configuration of harvested areas affect growth, but in structurally complex forests, tree-level variables such as species, initial DBH, and spatial position are more predictive than stand level characteristics (Biging & Dobbartin, 1995; McDowell *et al.*, 2003; Wiser *et al.*, 2004; Jones & Thomas, 2004). Silvicultural systems also offer tools for adapting to climate change. Retaining shelter trees, constructing fire lines, and implementing water conservation practices can mitigate heat and moisture stress, supporting regeneration and sustained growth (Ols & Bontemps, 2021; Kaarakka *et al.*, 2021). Adaptive silviculture, through practices like spacing and moisture management, is therefore essential to maintain forest resilience under shifting climatic conditions.

In Nepal's Terai lowlands, where forest site conditions, species composition, and management regimes (e.g., community and collaborative forestry) vary widely, assessment of the impacts of silvicultural systems on DBH growth is both timely and necessary. These interacting variables collectively influence tree development and forest productivity. Understanding how growth varies across DBH classes and species, and under different silvicultural and management contexts, is crucial for formulating climate smart and site-specific management strategies. Furthermore, since DBH is directly linked to stem volume and carbon storage, such assessments contribute to climate mitigation planning and carbon accounting (Bowler *et al.*, 2010).

This study assessed and compared annual diameter growth rate of different species managed under shelterwood and selection silvicultural systems in the Terai forests of Nepal, specifically within Madhesh Province. Further, it investigated the influence of key variables that included site condition, species, DBH class, and forest management regime on the diameter growth. The findings will inform evidence-based forest management and contribute to optimizing silvicultural interventions for ecological sustainability and economic benefit.



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2. Objectives

The primary objective of the study was to study the growth of forests under different silvicultural systems in Madesh Province, Nepal.

The specific objectives were to:

- Estimate the growth rate of forests, particularly diameter at breast height (dbh), over different time periods,
- To assess the differences in tree growth across shelterwood and selection system,

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3. Materials and methods

3.1 Study Sites

The study was conducted in Bara and Rautahat district of Madesh province. The study was conducted both in community forestry and collaborative forests where silvicultural system has been implemented.

Table 1: Study Sites

Silvicultural System	Variables	Location
Shelterwood	Mother tree	- Janaekata Community Forest, Rautahat - Hatemalo Community Forest, Rautahat - Janajyoti Community Forest, Bara
Selection	Selective measured trees for felling	- Janaekata Community Forest, Rautahat - Janasrijanshil Community Forest, Bara - Gadhimai Collaborative Forest, Bara

3.2 Data Collection

As the aim of the study was to assess the diameter growth of trees, we employed a repeated-measures approach by recording the Diameter at Breast Height (DBH) at two distinct time points, following standard forestry measurement protocols.

3.2.1 Measurement Protocol

During the initial measurement, DBH was measured at 1.3 meters above the ground using a diameter tape. All measurements were taken to the nearest 0.1 cm. After the first measurement, trees which were measured were permanently marked and numbered for future reference to ensure consistency in subsequent measurements. During the follow-up measurements, trees with identified permanent marks and number were only remeasured.

3.2.2 Measurement Periods

DBH measurements were taken during two different time periods. The time span between two measurements varied by site from 5 to 8 years (Table 2). The same trees were re-measured during the second time period to ensure accurate estimation of individual growth. The follow-up measurement was conducted in the same year but the initial measurement varied.

Table 2: Site and year of diameter measurements

S N	Site	First measurement year	Second Measurement year	Time span
1	Hatemalo Coupe 1	2075	2082	7
2	Hatemalo Coupe 2	2076	2082	6
3	Hatemalo Coupe 3	2077	2082	5
4	Janaekata	2076	2082	6
5	Janajyoti	2074	2082	8
6	Janashrijansil CF	2076	2082	6
7	Gadimai CFM	2074	2082	8
		2075	2082	7
		2076	2082	6
		2077	2082	5
8	Hatemalo CF (Chapur)	2075	2082	7

3.2.3 Data Recording

For each tree, the attributes recorded were: tree ID, species, initial DBH, follow up DBH, DBH class, site location, silvicultural system, and management regime. Trees with damage or measurement inconsistencies were excluded from the analysis. During the follow-up measurements more than 2800 trees/poles that were measured initially were remeasured. In the next phase, data cleaning was done to remove trees that were unfirmed, and where measurement errors were observed. After the data cleaning, the final number of poles/trees analyzed were 2432 only. The initial measurements of data were provided by respective forest units and divisional forest offices whereas the research team implemented the follow-up measurements.

In this study, the “mother” or “shelter” trees retained for future harvesting or for seed dispersal under shelterwood systems were measured (Pokhrel *et al.*, 2024). Trees which were marked for selective cutting and which had no other basis for their selection rather than individual selection were considered for selection system.



3.3 DBH Growth Calculation

DBH growth percentage and annual growth rate was calculated using the following formula.

Diameter Growth Percentage (DGP)

$$DGP = \left(\frac{D2 - D1}{D1} \right) \times 100$$

Annual Growth Rate (AGR)

$$AGR = \frac{D2 - D1}{n}$$

Where,

D1 is the DBH measured during initial measurement in cm

D2 is the DBH measured during follow-up measurement in cm

n is the time span between two measurements in years

Annual Growth Rate was used as the dependent variable in subsequent statistical analyses.

3.4 Diameter Growth Modeling

Individual tree modeling is a foundational approach to study natural forest growth. Linear mixed effects model was used to assess the influence of multiple factors, where site conditions, management regime, silvicultural system, tree species and diameter class were included as fixed effects, while sit-level variability was treated as random effects influencing the annual growth rate (AGR) of diameter at breast height (DBH), and to quantify their individual and combined effects on DBH growth. As the data were collected from multiple geographic sites, there was a possibility that observations within the same site were more similar to each other than to those from other sites. Therefore, the inclusion of site as a random effect in the model allowed for control of this hierarchical structure and partitioned out the variance due to site-specific conditions, which could otherwise bias the estimation of fixed effects. LMM provided more accurate and generalizable inferences about how forest management and ecological factors influence tree growth across the study sites.

As we had many species, we grouped less frequent species, and kept major four species stand alone. Further, we tested the performance of reduced model removing species variable with the



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full mixed model performance, and evaluated based on AIC values. The model with less AIC value was the desired model to assess the annual diameter growth rate.

3.5 Statistical analysis

Linear mixed effect model analyses were used to test for the effects of possible influences on diameter growth rate. Diameter growth rate (cm year⁻¹) for a given individual tree during calendar year was the response variables in the linear mixed models. Management regime, silvicultural system, species, site and their interaction were employed as fixed-effect explanatory variables in the model. Possible combinations of the explanatory variables were tested. For the linear mixed effect model analyses, the function 'lmer' of the package 'lme4' from the statistics package R version 4.5.0 Patched (R Core Team, 2025) was used.

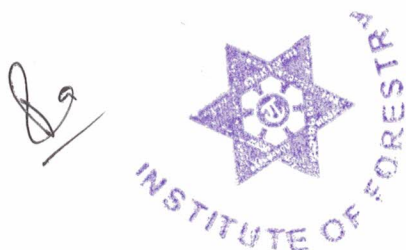
ANOVA test was conducted to determine the influence of independent variables on dependent variable, i.e., annual diameter growth rate. The post-hoc analysis (Tukey's Honest Significant Difference) was conducted after a significant ANOVA result to identify which specific groups had significantly different means in Annual Growth Rate (AGR).

Mathematical equation of the model

$$AGR_{ij} = \beta_0 + \beta_1 \cdot \text{mgmtregime}_{ij} + \beta_2 \cdot \text{silvisystem}_{ij} + \beta_3 \cdot \text{sppcode}_{ij} + \beta_4 \cdot \text{dbh1class}_{ij} + u_j + \epsilon_{ij}$$

Where:

- AGR_{ij} : Annual diameter growth of tree i in site j
- β_0 : Fixed intercept (baseline growth)
- $\beta_1, \beta_2, \beta_3, \beta_4$: Fixed effect coefficients for:
 - mgmtregime: Management regime
 - silvisystem: Silvicultural system
 - sppcode: Species code
 - dbh1class: Diameter class
- $u_j \sim N(0, \sigma_u^2)$: Random intercept for sitecode (site-level variability)
- $\epsilon_{ij} \sim N(0, \sigma^2)$: Residual error for individual tree observations



4. Results and discussion

4.1 Descriptive statistics of DBHs measured during two periods

The descriptive statistics of diameter at breast height (DBH) measurements during the two periods provide insights into tree growth (Table 3). The mean annual diameter growth rate (AGR) was 0.79 cm, standard deviation of AGR was 0.59 and the coefficient of variation (CV) of AGR was relatively high at 0.75, reflecting diverse growth rates across individual trees. The initial DBH (dbh1) had a mean of 55.42 cm and showed moderate dispersion (CV = 0.35). The follow-up DBH (dbh2) increased to a mean of 60.16 cm, with a similar spread (CV = 0.33), confirming an overall increase in tree diameter. The interquartile range (IQR) of dbh1 and dbh2 indicated consistent growth across most of the sampled trees. These statistics collectively reflect a positive trend in tree diameter growth over the measurement period. The nature of the DBH measured during the two periods can be visualized from the histograms (Figure 1 and Figure 2). The descriptive statistics of other factors used in this study is presented in Annex-1.

Table 3: Descriptive statistics of variable measured

Variable	Mean (unit)	Median	StdDev	Minimum	Maximum	Q1	Q3	IQR	CV
AGR	0.79	0.66	0.59	0.00	3.88	0.36	1.06	0.70	0.75
dbh1	55.42	52.84	19.24	21.37	168.00	39.79	66.60	26.81	0.35
dbh2	60.16	58.00	19.59	30.00	169.00	44.56	71.83	27.26	0.33

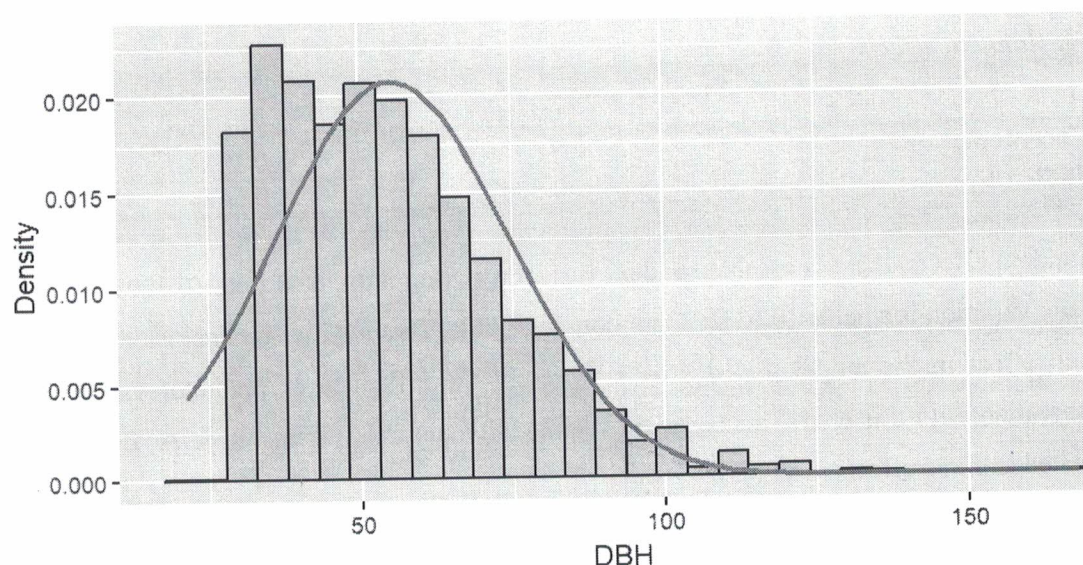


Figure 1: Histogram of initial DBH

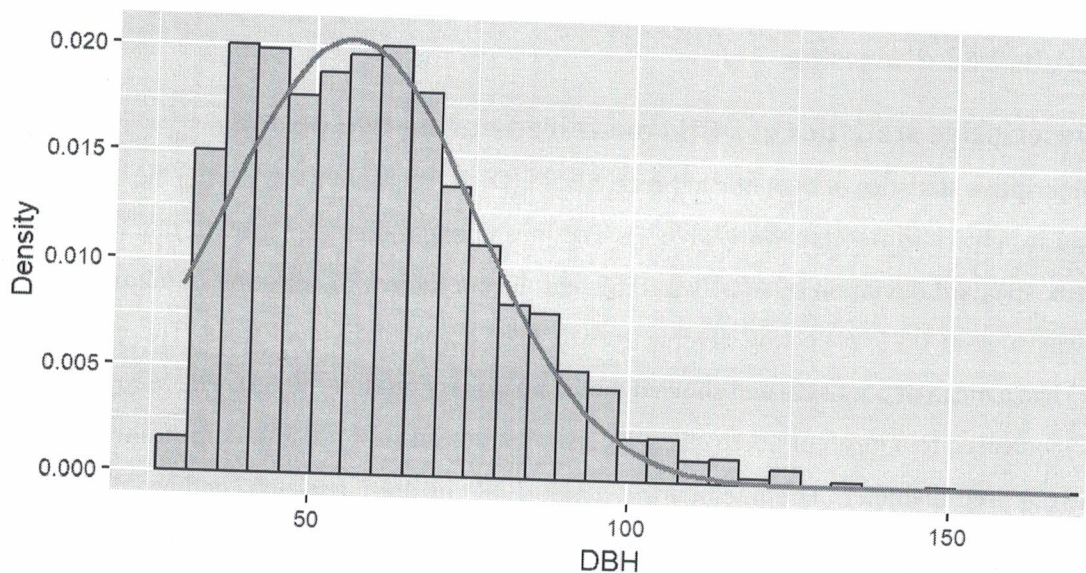


Figure 2: Histogram of follow-up DBH

4.2. Linear Mixed Effects Model

The Linear Mixed Effects Model (LMM) was run to see the influence of independent variables on dependent variable. In the model, site was treated as random effect. Random effects are used to account for variation in the data that arises from grouping or clustering. Treating site as a random intercept allowed each site to have its own baseline AGR (growth rate), accounting for environmental and management differences between sites. The summary of random effects is presented in table 4.

Table 4: Random effects

Effect	Variance	Std. Dev
Site (Intercept)	0.03182	0.1784
Residual	0.30075	0.5484

In the random effects, there is notable residual variation among individual trees (0.30075), while site-to-site variation is smaller (0.03182), but non-negligible. This justifies the inclusion of site as a random effect in the model. Fixed effects represent the influence of predictor variable on response variable. In this study, management regime, silvicultural systems, species, DBH class were treated as fixed effects (Table 5).

Table 5: Fixed effects

Predictor	Estimate	Std. Error	DF	t-value	Pr(> t)	Significance
Intercept	1.294	0.1363	12.94	9.496	3.39E-07	***
Management regime 2	0.1294	0.203	2.576	0.637	0.576	
Silvicultural system 2	-0.4041	0.062	630.9	-6.521	1.43E-10	***
Species 2	-0.263	0.0393	2410	-6.696	2.65E-11	***
Species 3	-0.3112	0.0539	2413	-5.772	8.84E-09	***
Species 7	-0.2702	0.0672	2414	-4.019	6.01E-05	***
Species 9	-0.306	0.063	2414	-4.856	1.27E-06	***
Species 20	-0.4039	0.0337	2317	-11.99	<2E-16	***
DBH class 2	-0.0238	0.0922	2413	-0.258	0.7965	
DBH class 3	0.0089	0.0938	2414	0.095	0.9243	
DBH class 4	0.0158	0.0948	2414	0.167	0.8677	
DBH class 5	-0.0408	0.0966	2414	-0.423	0.6726	
DBH class 6	-0.1601	0.0989	2414	-1.619	0.1056	
DBH class 7	-0.1105	0.104	2412	-1.064	0.2875	
DBH class 8	-0.1049	0.1147	2413	-0.916	0.3599	
DBH class 9	-0.1177	0.1393	2414	-0.846	0.3979	
DBH class 10	-0.1557	0.1703	2414	-0.915	0.3605	
DBH class 11	-0.2734	0.1627	2414	-1.681	0.0928	. (marginal)

Significance codes: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; . $p < 0.1$

In the fixed effects, the intercept for the estimated mean AGR for the reference levels of all categorical variables is 1.294. Compared to shelterwood system, there is significant decrease in AGR by 0.4041 units in selection system which is statistically significant ($p < 0.001$). All other species including the mix of species (species 20) have significantly lower AGR compared to Sal trees which is statistically significant ($p < 0.001$). The diameter class do not have a statistically significant impact on AGR at $p < 0.05$. Compared to community forestry, the collaborative forest management is not statistically significant ($p = 0.576$). This suggest that there is not clear effect of management regime on diameter growth rate in the forest.

The Linear Mixed Effects Model reveals that silvicultural system and species types have a strong, statistically significant influence on tree diameter growth (AGR), while management regime and diameter class show no significant effects. Including sites as a random effect is justified, as it captures variability between locations, though most variance is at the tree (residual) level. This model supports species and silvicultural system specific strategies for forest management for better

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growth performance of trees. The influence of individual factors is further explained in the subsequent sections.

4.3 Diameter growth at different sites

The study was conducted in two districts of Madesh Province; Bara and Rautahat districts. The sites for the study included both community forests and collaborative forests. The dominant species in all the site was sal, except in Janashrinshil CF where other species dominated sal. Table 6 provides the details of all the sites.

Table 6: Site details

SN	Forest unit	Location	Major species	Number of trees/poles measured
1	Hatemalo Community Forest	Rauthat district	Sal, Gingar	552
2	Janaekata Community Forest	Rauthat district	Sal, Jamun, Barro	67
3	Janajyoti Community Forest	Bara district	Sal	59
4	Janashrijanshil Community Forest	Bara district	Asna, Sal, Botdhairo	292
5	Gadimai Collaborative Forest	Bara district	Sal, Barro, Jamun	1462

The mean highest annual diameter growth rate (1.11cm/year) for all cumulative species was observed in Janaekata Community Forest and Janajyoti Community Forest whereas the mean lowest annual diameter growth rate (0.67cm/year) was observed in Hatemalo Community Forest. The annual diameter growth rate of all sites is presented in table 7.

In both Janaekata and Janajyoti CF, the trees measured were mostly mother trees. Due to the availability of abundant light and space, the growth rate was higher in both of these sites. On the other hand, the sample size is less in both of these sites, this could have also affected the results of this study.

Table 7: AGR by sites

Site	Count	Mean_AGR	SD_AGR	Min_AGR	Max_AGR
Hatemalo CF	552	0.67	0.46	0.00	3.18
Gadimai CFM	1462	0.85	0.61	0.00	3.88
Janaekata CF	67	1.11	0.86	0.00	3.67
Janasrijanshil CF	292	0.58	0.47	0.00	2.75

Janajyoti CF	59	1.11	0.65	0.09	2.99
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The trend of AGR (cm per year) by diameter class for the sites is different. This trend is illustrated through figure 3. In figure 3, each dot represents an individual tree with color distinguishing the sites. Superimposed trend lines (linear regression fits) for each site illustrate the general pattern of AGR change with increasing DBH. From the figure, it can be observed that Hatemalo CF has a slightly increasing AGR trend with DBH, indicating that growth may modestly improve with diameter. Gadimai CFM has a weakly negative trend, suggesting a slight decline in AGR as DBH increases. Janaekata CF and Janasrijanshil CF both show a mild positive relationship, with AGR tending to increase with DBH. Janajyoti CF has slightly negative trend. Overall, the figure shows how the relationship between DBH and AGR varied by site, reflecting differences in ecological conditions, management practices, or stand dynamics. This site-specific variation underlines the importance of localized analysis in forest growth assessments.

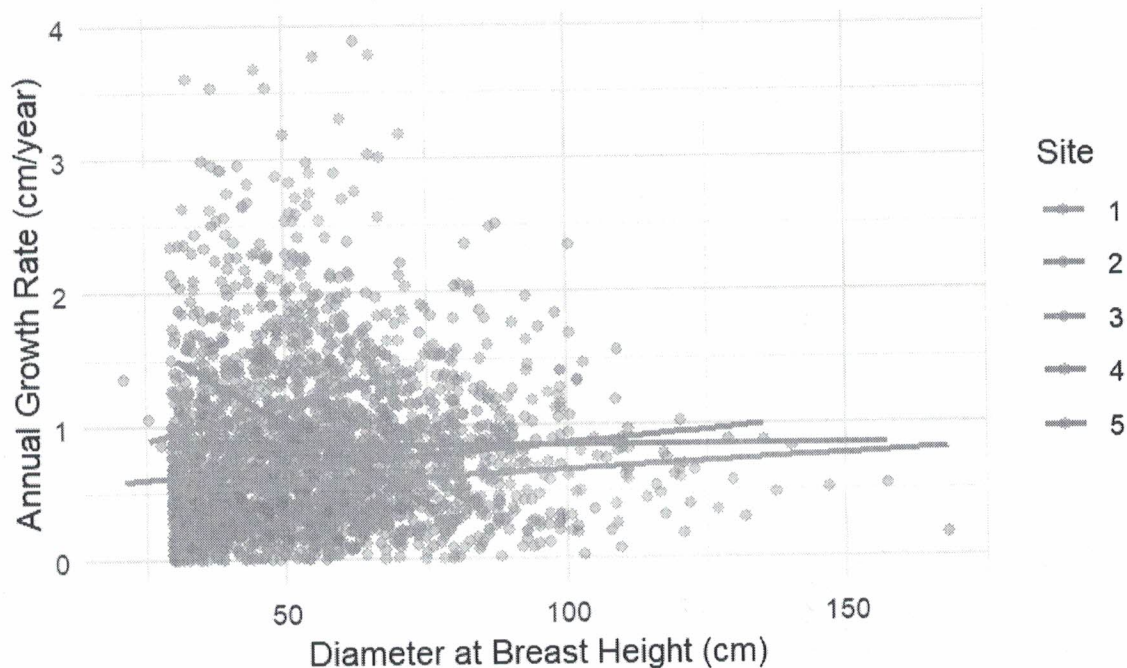


Figure 3: Trend of AGR by sites

While running the LMM model, some variability in the intercepts across sites was observed. The residual variance (0.30) was much larger than the site-level variance (0.03), indicating most

variation was within sites and not between sites. It indicates that factors like initial diameter, species and silvicultural systems might be more influential in tree growth rather than sites.

As sal is the major and valuable species for all the sites, we analyzed the rate and trend of diameter growth in sal species. For sal species, the highest mean annual growth rate (1.43cm/year) was observed in Janaekata Community Forest (table 8). In both Janaekata and Janajyoti CF, the sample trees measured were mostly mother trees which have better growth rate than others.

Table 8: AGR by sites for Sal

Site	Species	Count	Mean_AGR	SD_AGR	Min_AGR	Max_AGR
Hatemalo CF	Sal	394	0.76	0.45	0.00	3.18
Gadimai CFM	Sal	892	0.97	0.59	0.00	3.78
Janaekata CF	Sal	40	1.43	0.92	0.00	3.67
Janasrijanshil CF	Sal	22	0.74	0.52	0.05	2.08
Janajyoti CF	Sal	54	1.15	0.66	0.09	2.99

From figure 4, it can be observed that AGR for sal is generally decreasing with increasing DBH across most sites, especially in Gadimai CFM (site 2), Janaekata CF (site 3), Janasrijanshil CF (site 4), and Janajyoti CF (site 5), consistent with the biological pattern where larger/older trees show slower diameter growth. Haatemalo CF shows a slightly increasing or stable trend, which might suggest different management practices, site conditions, or age structure. Gadimai CFM has the highest data density, indicating more sampling, with a subtle declining trend. The blue lines represent fitted linear models, and gray shading shows confidence intervals, suggesting model certainty in predictions. In figure 4, Sites 1=Hatemalo CF, Site 2=Gadimai CFM, Site 3=Janaekata CF, Site 4=Janasrijanshil CF, Site 5=Janajyoti CF and AGR is in cm/year while the unit of DBH is cm.



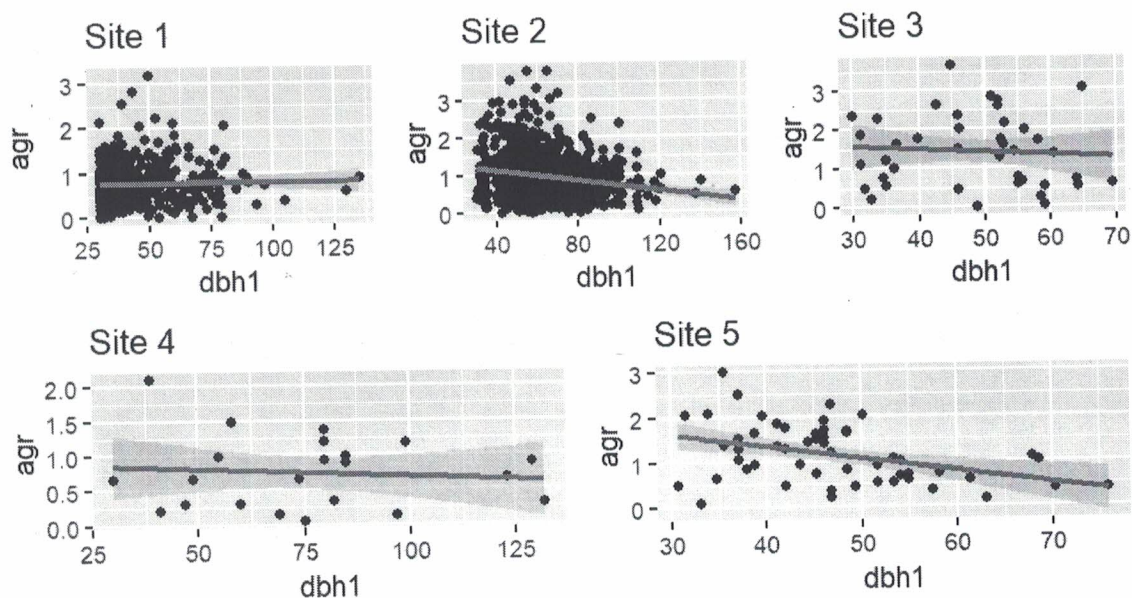


Figure 4: AGR of Sal by sites

4.4 Diameter growth under different management regime

Table 9: AGR under management regime

Management Regime	Count	Mean_AGR	SD_AGR	Min_AGR	Max_AGR
CF	970	0.70	0.54	0	3.67
CFM	1462	0.85	0.61	0	3.88

The annual diameter growth rate (0.85cm/year) for cumulative species was higher in collaborative forest management when compared with community forests (AGR=0.70 cm/year; table 9). The trend line shows the relationship between tree diameter and growth rate (Figure 5). In the CF, the trend line is nearly flat, suggesting that there is no strong relationship between tree diameter and growth rate; larger trees grow at similar rates to smaller ones. On the other hand, in the CFM, the trend line shows a clear negative slope, indicating that as DBH increases, the annual growth rate tends to decrease. This suggests that under the CFM regime, smaller trees are growing relatively faster than larger ones. This may be due to active management of forest in CFM as compared to CF. From figure 5 we can interpret that growth dynamics differ by management regime, with CFM showing a stronger size-dependent decline in growth. This may reflect differing silvicultural interventions, stand densities, or species compositions under each regime.

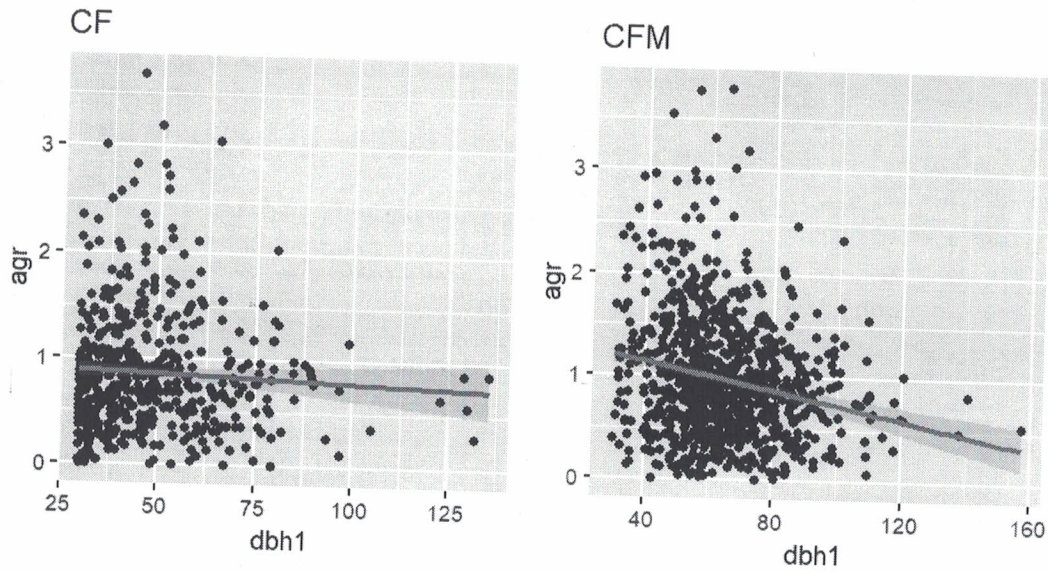
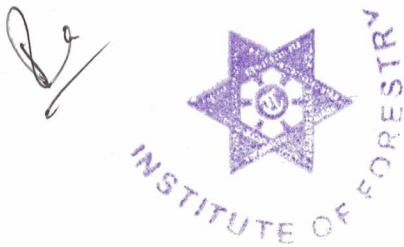


Figure 5: Trend of AGR by management regime



Furthermore, Figure 6 illustrate the relationship between diameter at breast height and annual diameter growth rate under two forest management regimes. In figure 6, community forests are denoted by 1 and collaborative forest by 2.



Figure 6: Relationship of AGR by management regime

4.5 Diameter growth under different silvicultural systems

The annual diameter growth (AGR) of trees managed under shelterwood system and selection system is significantly different. Forests managed under selection system exhibit significantly lower annual growth rates compared to those managed under shelterwood system, as indicated by a statistically significant negative coefficient in the linear mixed-effects model (Estimate = -0.4041, $p < 0.001$). This suggests that the management practices or interventions implemented under selection system is less conducive to promoting diameter growth, potentially due to higher competition. In contrast, shelterwood system appears more favorable for enhancing tree diameter increment, it may be due to less competition between individual trees. These findings emphasize the importance of silvicultural choice in influencing forest productivity and support the adoption of growth enhancing silvicultural system in forest management. This can be visualized from the box plots (Figure 7; where 1=Shelterwood system; 2=Selection system).

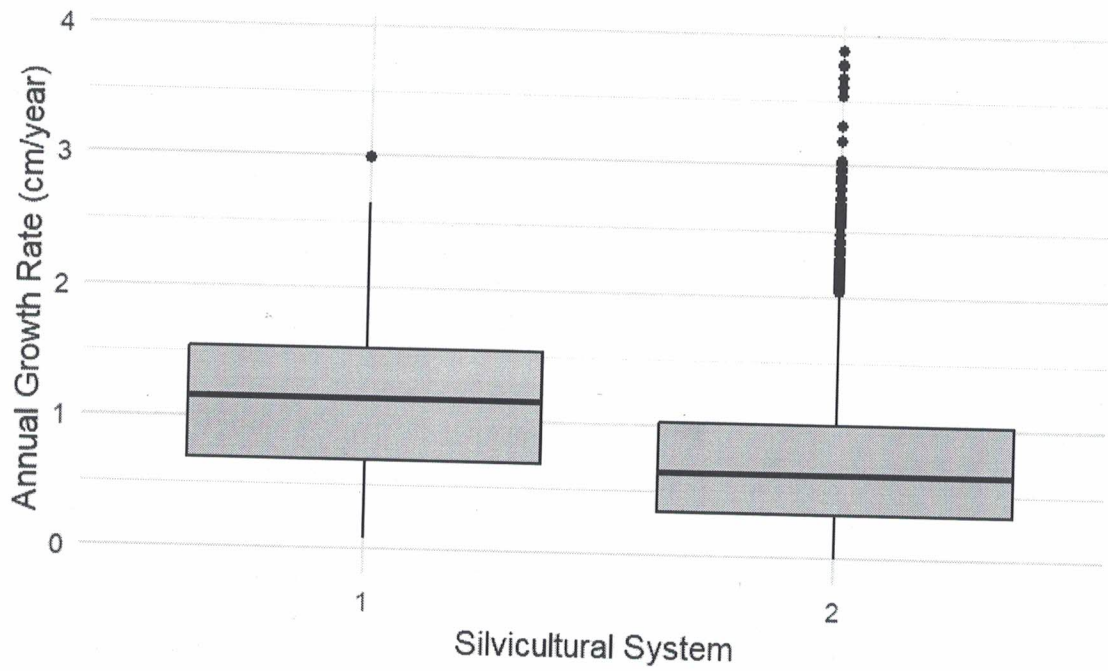
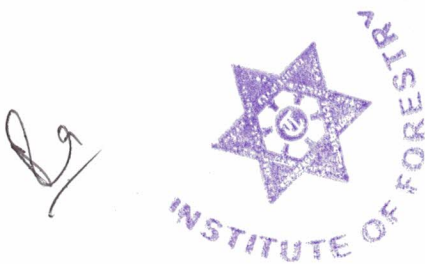


Figure 7: AGR by silvicultural system



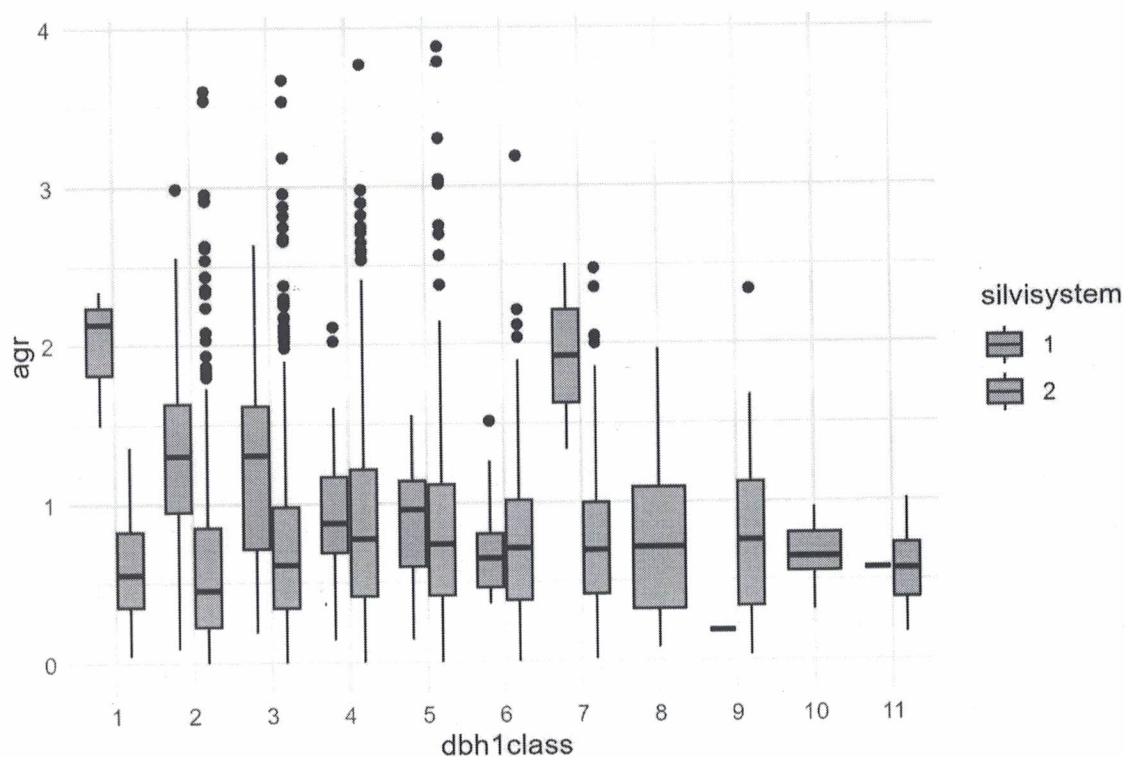


Figure 8: Comparison of AGR by silvicultural system and DBH class

Further, from figure 8 (1=Shelterwood system; 2=Selection system), it can be understood that there is a clear interaction effect between DBH class and silvicultural system on AGR. Shelterwood system supports rapid growth in younger/smaller trees, but this effect diminishes or is absent in larger DBH classes. Selection system provides more consistent growth across DBH classes, possibly indicating a more even-age or selective management regime. The trend line in figure 9 shows the distinction in growth rate by diameter in both silvicultural systems.



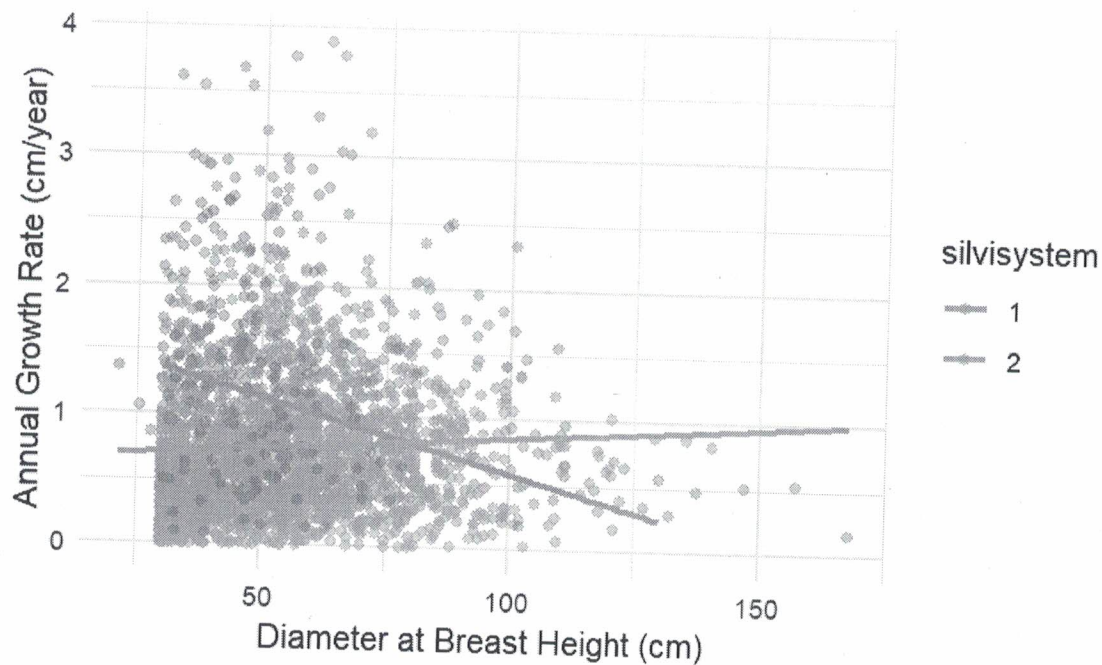


Figure 9: Trend of AGR by silvicultural system

4.6 Diameter growth by diameter class

Diameter class was categorized based on the diameter at breast height (DBH) measurements of individual trees of the initial measurement. The diameter class was grouped into predefined intervals of 10 cm class width, for example trees greater than 20 cm to 30 were grouped into class 1, 30-40 cm in class 2 and so on. The last diameter class consisted of trees with diameter 120 cm and above. This classification simplified continuous DBH data into discrete categories, making it easier to analyze patterns of growth across size classes and to compare growth performance among different cohorts of trees.

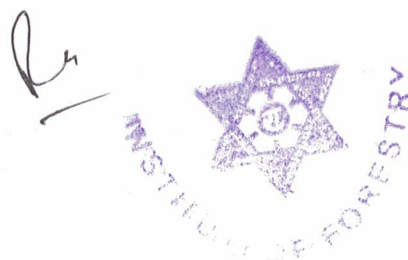
The annual diameter growth (AGR) which is presented in cm/year varied across different diameter classes, though the relationship was not consistently strong. In the linear mixed-effects model, most diameter class coefficients were not statistically significant, suggesting that diameter class alone may not be a strong predictor of annual growth rate. However, the overall trend indicates that trees in smaller diameter classes to mid class tend to exhibit slightly higher AGR compared to those in larger classes. For instance, the estimated coefficients for larger diameter classes (e.g.,

diameter class 8 to diameter class 11; table 10) are generally less, suggesting a decline in growth rate as tree diameter increases. This is a typical forest growth dynamic, where middle class trees often have higher relative growth rates than mature, larger trees.

Table 10: AGR by diameter class

DBH Class	Class range	Count	Mean_AGR	SD_AGR	Min_AGR	Max_AGR
1	>20 -<30	39	0.68	0.52	0.05	2.35
2	>=30 -<40	580	0.68	0.60	0.00	3.60
3	>=40 -<50	462	0.81	0.62	0.00	3.67
4	>=50 -<60	501	0.89	0.63	0.00	3.77
5	>=60 -<70	342	0.85	0.58	0.00	3.88
6	>=70 -<80	238	0.77	0.48	0.00	3.19
7	>=80 -<90	143	0.80	0.51	0.01	2.51
8	>=90 -<100	67	0.76	0.49	0.08	1.97
9	>=100 -<110	28	0.77	0.56	0.03	2.34
10	>=110 - <120	15	0.66	0.18	0.31	0.97
11	>=120	17	0.57	0.25	0.17	1.02

Figure 10 further visualize how the trend of annual diameter growth rate varies with diameter class. The figure presents the relationship between DBH (cm) and AGR (cm/year) across different DBH Classes (1 to 11), each represented by a distinct color. Each point in the plot represents an individual tree's AGR and DBH value. A general trend is observed where AGR decreases with increasing DBH, indicating that smaller trees grow faster annually than larger ones. This is a common growth pattern in natural forests, where younger or smaller trees tend to allocate more energy to growth. The overlaid colored trend lines for each DBH class further emphasize this declining pattern, especially beyond DBH 100 cm (classes 10 and 11), where AGR visibly drops. Overall, the plot highlights a negative relationship between tree size and growth rate, supporting the ecological understanding that growth rates taper off as trees mature.



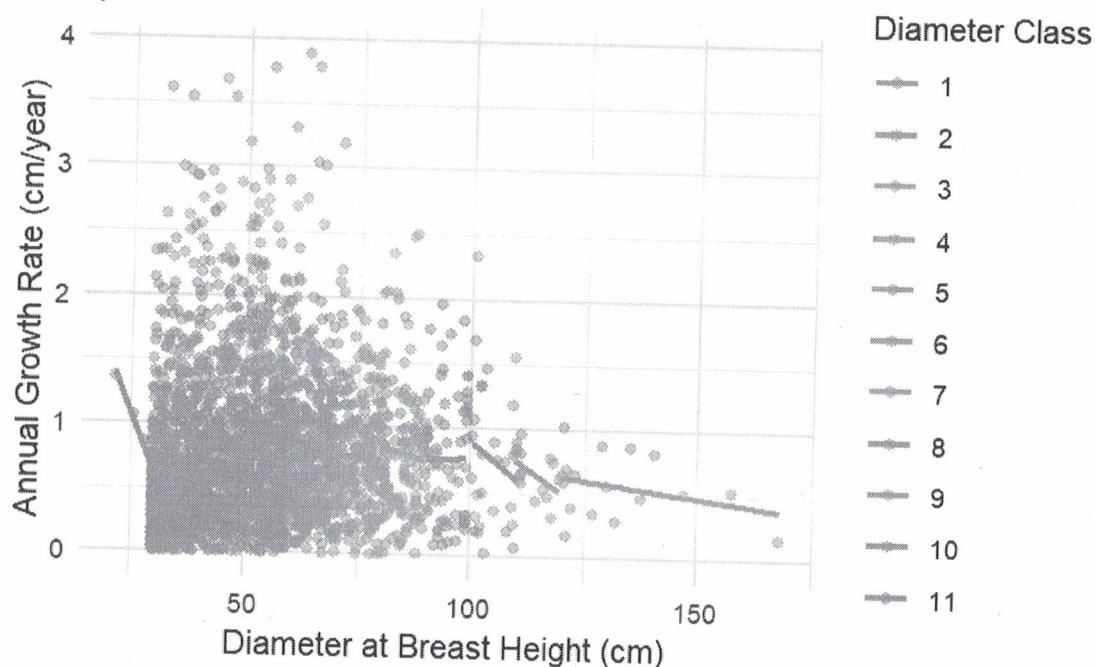


Figure 10: Trend of AGR by diameter class

The boxplot (Figure 11) illustrates the distribution of Annual Growth Rate (AGR) across 11 different diameter classes of trees. It is clear from the boxplot that AGR tends to vary across diameter classes. The middle diameter classes (particularly classes 3 to 5) show slightly higher median AGR compared to the lowest and highest classes. Younger/smaller trees (Diameter Classes 1–3) show a wider range of growth variability, including more extreme values (outliers), possibly due to the rapid early-stage growth of juvenile trees. Larger trees in Classes 10 and 11 show lower median AGR and less variation, suggesting that tree growth slows down as they mature. Outliers are visible in all diameter classes, especially in Classes 2 to 5, indicating that some individual trees in these classes grow much faster than the average. These trends can help guide silvicultural decisions, such as selecting target trees for thinning or monitoring growth in specific diameter cohorts.

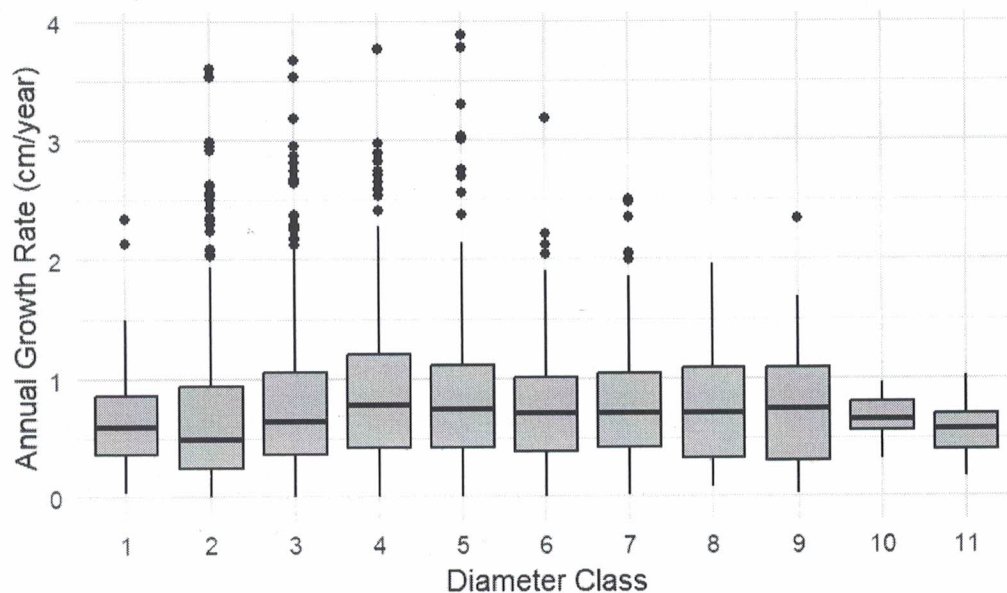


Figure 11: Comparison of AGR by diameter class

4.7 Diameter growth of different tree species

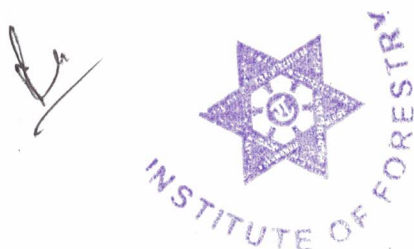
Out of 2432 trees measured, 1402 were sal, 255 Asna, 119 Jingar, 73 Jamun, 86 Barro and 497 were mix of other species. The analysis of annual growth rate (AGR) by species reveals significant differences in diameter growth among various tree species in the study sites. Using a linear mixed-effects model, with site as a random effect, the model showed that all other species had significantly lower AGR compared to the reference species *Shorea robusta*. The diameter growth rate of Asna, Jamun and Barroo exhibited significantly negative coefficients, indicating that these species experienced lower diameter growth rates over time. These results indicate that species-specific growth patterns should be carefully considered in silvicultural planning and forest management decisions, particularly when aiming to maximize forest productivity in sustainable forest management.

Table 11: AGR of different species

Species	Count	Mean_AGR	SD_AGR	Min_AGR	Max_AGR
Sal	1402	0.93	0.59	0.00	3.78
Asna	255	0.63	0.52	0.00	3.88
Jingar	119	0.67	0.57	0.01	2.60
Jamun	73	0.71	0.60	0.05	2.92
Barro	86	0.67	0.62	0.07	3.60

Further, figure 12 illustrates the variation AGR across five different tree species labeled as 1, 2, 3, 7, 9, and one mix of all other species labeled as 20. Species 1 (Sal) exhibits the highest median AGR and a wider interquartile range (IQR), indicating greater variability in growth compared to the other species. It also shows a significant number of high outliers, suggesting that some individuals in this species grow exceptionally fast. The remaining species have lower and more consistent AGR values, with medians clustered between approximately 0.5 and 0.8. Their IQRs are narrower, and while they also exhibit outliers, these are fewer and less extreme than those in sal. Overall, figure 12 suggests species-level differences in growth performance, with sal demonstrating superior growth potential under the given environmental and management conditions. The result of the mean annual diameter growth rate of 0.93 cm per year for sal is close with past studies conducted in Terai region of Nepal in Chitwan district where the mean annual diameter growth rate was reported to be 0.87cm/year (Sapkota and Meilby, 2010).

The mean Diameter Growth Percentage (DGP) was highest for Sal (10.80%), followed by Barro (9.04%), Jingar (8.50%), Jamun (7.93%) and Asna (6.40%).



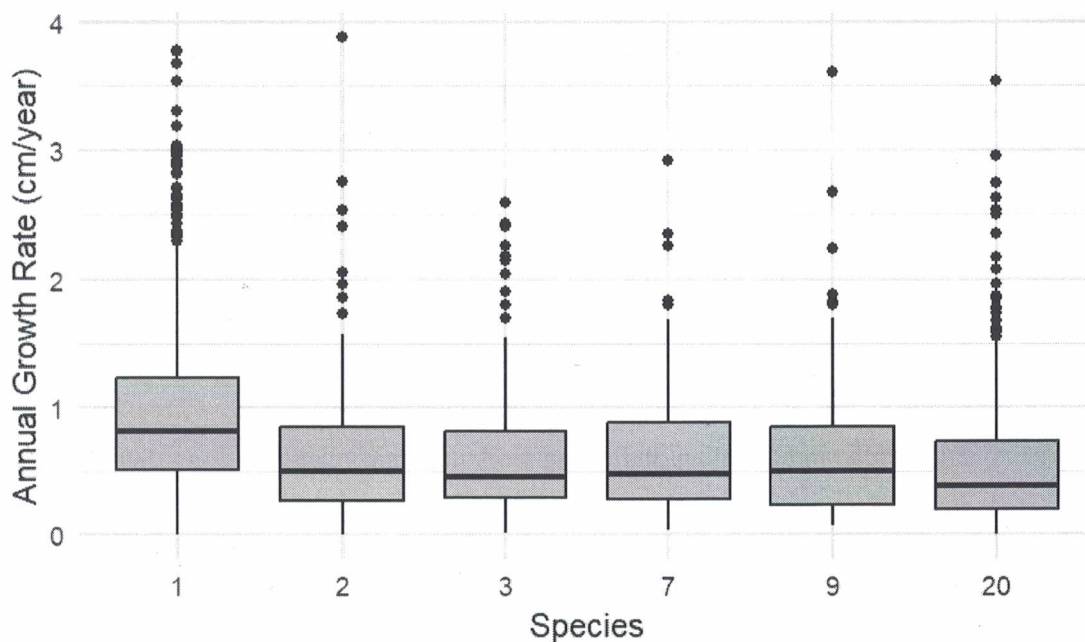


Figure 12: Comparisons of AGR by species

4.7.1 Diameter growth of Sal by sites

Sal is the most dominant species in all the sites except in Janasrijanshil CF. The analysis of annual growth rate (AGR) for sal across the sites revealed statistically significant variation in growth performance. Janaekata CF exhibited the highest AGR, followed by Janajyoti CF and Gadimai CFM, while Hatemalo CF and Janashrijanshil showed comparatively lower growth rates. Tukey's post-hoc test confirmed that the differences between Janaekata CF and all others (except Janajyoti) were statistically significant, indicating that site-specific factors influenced the growth of trees. These findings highlight the importance of site selection and localized forest management to optimize tree growth and productivity for sal.

Table 12: AGR of sal in different sites

Site	Species	Count	Mean_AGR	SD_AGR	Min_AGR	Max_AGR
Hatemalo CF	Sal	394	0.76	0.45	0.00	3.18
Gadimai CFM	Sal	892	0.97	0.59	0.00	3.78
Janaekata CF	Sal	40	1.43	0.92	0.00	3.67
Janashrijansil CF	Sal	22	0.74	0.52	0.05	2.08
Janajyoti CF	Sal	54	1.15	0.66	0.09	2.99



How growth patterns for sal varied across different sites is visualized in figure 13. The figure illustrates the relationship between DBH and AGR of trees, disaggregated by sites using LOESS smoothing curves. The use of LOESS smoothing allows for capturing non-linear trends and offers a clearer understanding of the diameter-growth dynamics across different forest sites. Site 3 (green line) shows a strong peak in growth rate around 40–50 cm DBH, indicating that trees at this site grow fastest at medium sizes and then decline in growth as they get larger. Site 5 (pink line) and Site 1 (red line) also exhibit moderate peaks in AGR around 40–60 cm DBH, but with more modest growth rates than Site 3. Site 2 (olive line) has a flatter curve, suggesting more stable and moderate growth across a wide range of diameters. Site 4 (blue line) shows a slightly increasing trend up to around 70 cm, then a slight decline, indicating trees maintain relatively consistent growth rates until larger sizes. The general trend shows that AGR tends to decline as DBH increases, indicating slower growth rates in larger trees. However, the exact pattern varies by site, suggesting that site-specific factors such as soil quality, management regime, or silvicultural practices may influence growth. This visualization helps identify optimal DBH ranges for harvesting or intervention, and supports site-based silvicultural planning to enhance productivity. In figure 13, site code 1 is for Hatemalo CF, 2 for Gadimai CFM, 3 for Janaekata CF, 4 for Janashrijansil CF and 5 for Janajyoti CF.

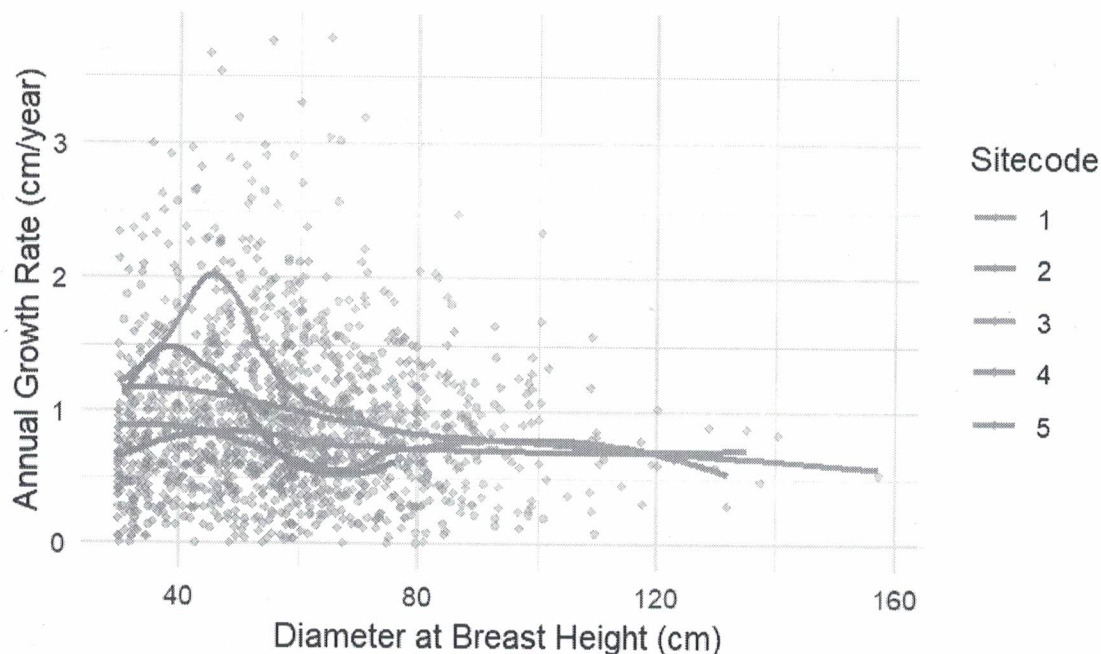


Figure 13: Trend of AGR of sal in all sites



To evaluate the site effects on AGR of sal trees, we further conducted ANOVA.

Table 13: ANOVA table of site effects on AGR

Source	Df	Sum Sq	Mean Sq	F value	Pr(>F)	Significance
Factor(site)	4	25.7	6.437	19.77	7.65e-16	***
Residuals	1397	454.9	0.326			

The mean AGR is the same across all site's codes. The F value of 19.77 is quite high, indicating strong evidence that at least one site has a significantly different mean AGR. The p value is very small, leading us to reject null hypothesis. Thus, there is significant differences in AGR among different site for sal.

To understand which specific pairs of sites had statistically significant difference in mean AGR, following the ANOVA on AGR across sites for *Shorea robusta*, we conducted post-hoc analysis: Tukey's Honest Significant Difference (HSD) test.

Table 14: Turkey's HSD test

Comparison	Mean Difference	95% CI (Lower - Upper)	Adjusted p-value	Significance
Site 2 vs Site 1	+0.208	0.114 – 0.302	< 0.0001	Significant
Site 3 vs Site 1	+0.663	0.404 – 0.922	< 0.0001	Significant
Site 4 vs Site 1	–0.022	–0.363 – 0.320	0.9998	Not Significant
Site 5 vs Site 1	+0.389	0.163 – 0.615	0.00003	Significant
Site 3 vs Site 2	+0.455	0.203 – 0.707	0.00001	Significant
Site 4 vs Site 2	–0.230	–0.566 – 0.107	0.337	Not Significant
Site 5 vs Site 2	+0.181	–0.038 – 0.399	0.158	Not Significant
Site 4 vs Site 3	–0.685	–1.098 – –0.271	0.00007	Significant
Site 5 vs Site 3	–0.274	–0.599 – 0.051	0.145	Not Significant
Site 5 vs Site 4	+0.411	0.016 – 0.805	0.036	Significant

(Site 1= Hatemalo CF, Site 2= Gadimai CFM, Site 3= Janaekata CF, Site 4= Janashrijansil CF, Site 5= Janajyoti CF)

Site 3 (Janaekata CF) showed consistently higher AGR than 1 (Hatemalo CF), 2(Gadimai CFM), and 4 (Jansrijanshil CF) and is significantly different from all of them. Site 5 (Janajyoti CF) also has significantly higher AGR than site 1 and 4. Site 3 seems to be the most productive in terms of tree diameter growth (AGR) of *Shorea robusta*.

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4.7.2 Diameter growth of sal by dbh class

To examine whether diameter growth varied across different diameter class, ANOVA test was conducted.

Table 15: ANOVA table of AGR by diameter class

Source	Df	Sum Sq	Mean Sq	F value	Pr(>F)	Significance
Factor (dbh class)	10	11.0	1.1037	3.269	0.000343	** (highly significant)
Residuals	1391	469.6	0.3376			

The analysis shows that DBH class has a statistically significant effect on annual diameter growth rate (AGR). At least one diameter class differs significantly from the others in terms of mean AGR, which requires post-hoc analysis (Tukey HSD) to identify which specific classes differ.

The Tukey HSD (Tukey's Honest Significant Difference) test is a post-hoc analysis conducted after a significant ANOVA result to identify which specific groups have significantly different means in Annual Growth Rate (AGR).

Table 16: HSD test of AGR by diameter class

Comparison	Difference (diff)	95% CI (lwr to upr)	Adjusted p-value	Interpretation
6-3	-0.1847	-0.368, -0.0015	0.0461	Class 6 has significantly lower AGR than Class 3
6-4	-0.1934	-0.367, -0.0198	0.0150	Class 6 has significantly lower AGR than Class 4

These are the only two comparisons with statistically significant differences at the 5% level. All other adjusted p-values are much greater than 0.05, meaning those differences in AGR across classes are not statistically significant.

Although the ANOVA showed an overall significant difference among DBH classes, the Tukey post-hoc test reveals that only a few class pairs (DBH Class 6 vs 3 and 6 vs 4) show a statistically significant difference in AGR. Most DBH class pairs do not differ significantly in mean growth, suggesting that the differences cannot be generalized. The rate of AGR by diameter class can be further visualized from Figure 14.

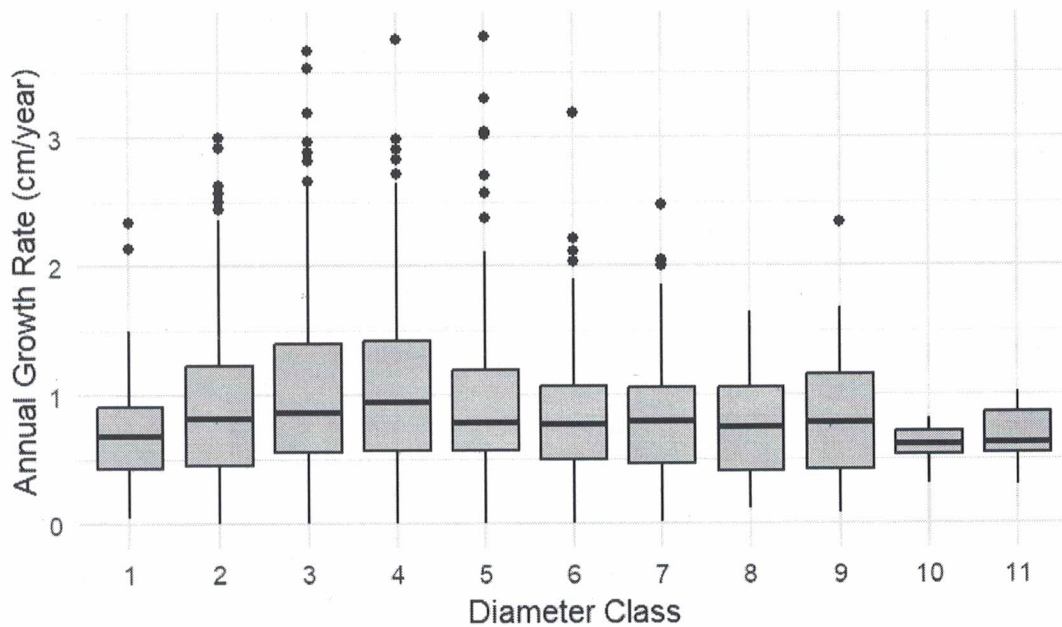


Figure 14: AGR by diameter class of Sal

4.7.3 Diameter growth of Asna by dbh class and sites

Asna was the second dominant species next to sal. We conducted ANOVA test to see whether AGR differed by diameter class in Asna.

Table 17: ANOVA table of AGR by diameter class

Source	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Factor(dbh class)	10	5.27	0.5269	2.046	0.0296
Residuals	244	62.84	0.2576		

There is a statistically significant difference in AGR among different diameter classes which indicate that diameter class does influence tree growth. However, since the p-value is only slightly below 0.05 and the F-value is moderate, the effect size may not be large, and further post-hoc tests (e.g., Tukey HSD) is required to determine which classes differ.

The Tukey HSD results showed that trees in diameter classes 4 and 5 grew significantly faster than those in class 2, but no other pairwise class differences were significant. This suggests that AGR is relatively stable across most DBH classes, with only a few exceptions where growth is noticeably higher. The rate of AGR by diameter class can be further visualized from Figure 15.



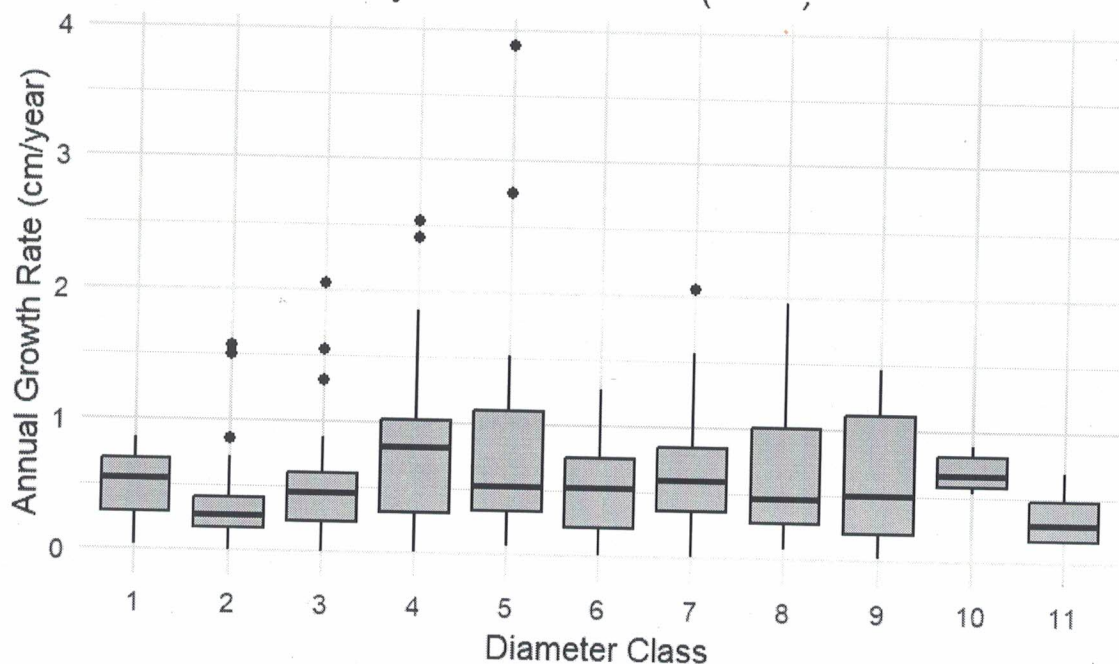


Figure 15: AGR by Diameter class of Asna

The rate of AGR by diameter differed by site as well. In Gadimai CFM and Janasrijanshil CF, AGR decreased with increasing diameter slightly where as in Hatemalo CF, AGR increased with increasing dbh slightly. The other two sites did not have sufficient number of Asna for statistical analysis.

Figure 16 is a scatter plot with LOESS smoothing lines, illustrating the relationship between DBH and AGR across three different forest sites for Asna. Trees in Site 1 tend to have lower AGR at smaller DBH values, a slight dip around 30 cm, then an increase in AGR around 55–65 cm DBH. Site 2 Shows a stable AGR trend between 0.5 to 1 cm/year across the DBH range (30–90 cm). There is a gentle increase and then slight decline, suggesting moderate growth that does not significantly change with increasing tree size. In site 4, AGR is higher at smaller diameters, gradually decreases with increasing DBH, showing a negative trend after 60–70 cm. These patterns highlight how site-specific factors (soil, management, species composition) influence growth dynamics.

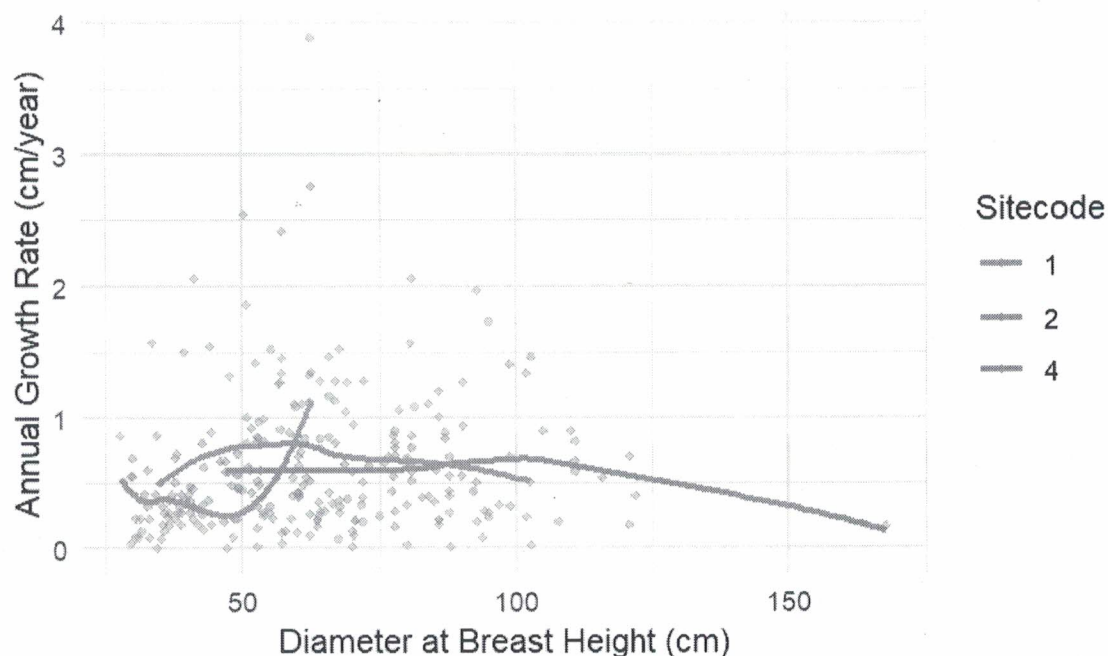


Figure 16: AGR by DBH class for Asna in all sites

5. Conclusion and recommendations

The study assessed the diameter growth of trees in Madesh Province, Nepal, with a focus on how growth is influenced by management regime, silvicultural system, species, diameter class, and site conditions. The mixed effects model employed in the study revealed that species and silvicultural systems had significant effects on the annual diameter growth rate (AGR), while site-level variation also played a notable role, as confirmed by the mixed-effect model incorporating random effects for sites. The diameter growth was better in shelterwood system than selection system. *Shorea robusta* showed substantial variation in growth across different sites, with Janaekata community forestry consistently exhibiting the highest growth performance. The mean annual diameter growth rate for all site for sal was found to be 0.93 cm/year with highest (1.43cm/year) in Janaekata community forest. This suggests that local site factors and silvicultural practices strongly influence tree productivity. The findings emphasize the importance of site-specific silvicultural system and species selection to enhance forest productivity and support sustainable forest management in the region. Based on our study, the key recommendations are;

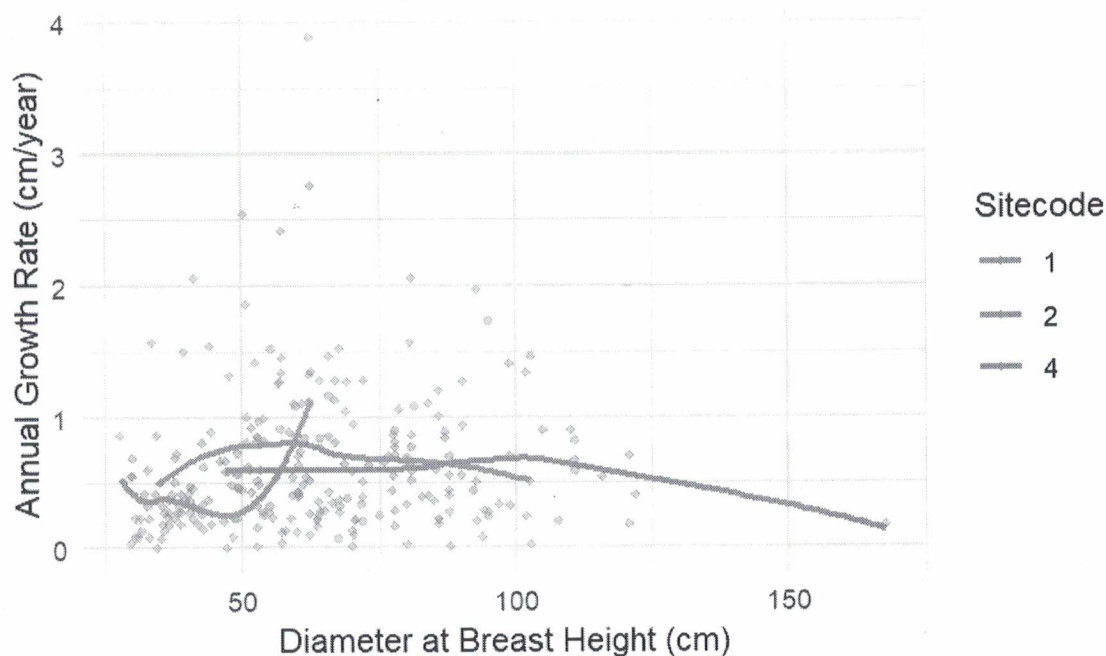


Figure 16: AGR by DBH class for Asna in all sites

5. Conclusion and recommendations

The study assessed the diameter growth of trees in Madhesh Province, Nepal, with a focus on how growth is influenced by management regime, silvicultural system, species, diameter class, and site conditions. The mixed effects model employed in the study revealed that species and silvicultural systems had significant effects on the annual diameter growth rate (AGR), while site-level variation also played a notable role, as confirmed by the mixed-effect model incorporating random effects for sites. The diameter growth was better in shelterwood system than selection system. *Shorea robusta* showed substantial variation in growth across different sites, with Janaekata community forestry consistently exhibiting the highest growth performance. The mean annual diameter growth rate for all site for sal was found to be 0.93 cm/year with highest (1.43cm/year) in Janaekata community forest. This suggests that local site factors and silvicultural practices strongly influence tree productivity. The findings emphasize the importance of site-specific silvicultural system and species selection to enhance forest productivity and support sustainable forest management in the region. Based on our study, the key recommendations are;

- **Adopt Shelterwood Systems:** Diameter growth was significantly high in shelterwood system, and while comparing the growth rate of available species, sal performed better. Therefore, shelterwood systems should be adopted in sal-dominated forests to maximize growth and productivity.
- **Species-Specific Management:** Tree growth is not uniform for all species in similar types of silvicultural system and sites. So, silvicultural system and practices adopted should be specific to species and site requirements. In high productive sites, economically valuable species like Sal should be given priority.
- **Exploitable size:** Tree size is a more direct indicator of individual tree vigor and site conditions. Trees that have reached a specific diameter threshold can be considered mature enough to be harvested sustainably. As beyond 70 cm DBH the growth rate slows down for Sal, determining 70 cm DBH as an exploitable size of Sal tree is recommended.
- **Site-Adaptive Strategies:** In order to optimize production of timber and other forest products in Madesh Province, the assessments of all types of forest should be conducted and localized adaptative strategies should be implemented for sustainable forest management.
- **Long-Term Monitoring:** Silvicultural interventions such as thinning, selective harvesting or regeneration methods directly influence forest structure, species composition, and individual tree growth. At the same time, climate change is altering temperature, precipitation patterns, and growing conditions. Continuous monitoring provides critical data that helps forest managers understand how different species and forest types are responding to these combined influences over time. Therefore, continuous monitoring to track growth responses to silvicultural practices and climate change is required.
- **Community Engagement:** The Terai forests are a critical source of timber and fuelwood for rural households. Engaging local communities ensures that forest management practices align with their needs, knowledge, and priorities, leading to more sustainable management practices and equitable outcomes.

References

- Ashton, M.S. and Keltj, M.J. (2018). *The Practice of Silviculture: Applied Forest Ecology*. 10th edition., John Wiley and Sons Ltd.
- Bianchi, S., Siipilehto, J., Repola, J., Niemisto, P., Korhonen, K., Peltoniemi, M., Salminen, H., Hynynen, J., (2023). Individual tree basal area increment models suitable for different stand structures in Finland. *Forest Ecology Management* 549, 121467. <https://doi.org/10.1016/j.foreco.2023.121467>
- Biging, G.S. and Dobberty, M. (1995). Evaluation of competition indices in individual growth models. *Forest Science* 41: 360-377.
- Biging, G.S. and Dobberty, M. (1995). Evaluation of competition indices in growth models. *Forest Science* 41: 360-377.
- da Silva, R.P., Santos, J., Tribuzy, E. S., Chambers, J. Q., Nakamura, S. and Higuchi, N. 2002. Diameter increment and growth patterns for individual tree growing in Central Amazon, Brazil. *Forest Ecology and Management*, 166: 295-301. [https://doi.org/10.1016/S0378-1127\(01\)00678-8](https://doi.org/10.1016/S0378-1127(01)00678-8).
- Ekholm, A., Axelsson, P., Hjalten, J., Lundmark, T. and Sjogren, J. (2022). Short-term effects of continuous cover forestry on forest biomass production and biodiversity: Applying single-tree selection in forests dominated by *Picea abies*. *Ambio*, 51:24. <https://doi.org/10.1007/s13280-022-01749-5>
- Jones, T.A. and Thomas, S.C. (2004). The time course of diameter increment responses to selection harvests in *Acer saccharum*. *Canadian Journal of Forest Research* 34: 1525-1533.
- McDowell, N., Brooks, J.R., Fitzgerald, S.A. and Bond, B.J. (2003). Carbon isotope discrimination and growth response of old *Pinus ponderosa* trees to stand density reductions. *Plant Cell Environment* 26(4): 631-644.
- McDowell, N., Brooks, J.R., Fitzgerald, S.A., Bond, B.J. (2003). Carbon isotope discrimination and growth response of old *Pinus ponderosa* trees to stand density reductions. *Plant Cell Environment* 26(4): 631-644.
- Pokhrel, N., Timilsina, S., Awasthi, N., Adhikari, A., Adhikari, B., Ayer, S. and Bhatta, K.P. (2024). Implication of irregular shelterwood system on regeneration and species diversity

of Sal (*Shorea robusta* Gaertn.f.) forest in Nepal. *Heliyon* 10.

<https://doi.org/10.1016/j.heliyon.2023.e23156>

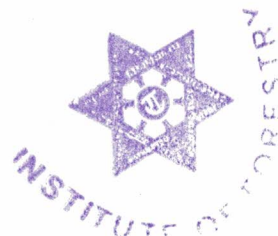
R Core Team (2025). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. <<https://www.R-project.org/>>.

Sapkota, P. and Meilby, H. (2010). Modelling the growth of *Shorea robusta* using growth ring measurements. *Banko Janakari* 19(2):25-32.

Wiser, S.K., Allen, R.B., Benecke, U., Baker, G. and Peltzer, D. (2005). Tree growth and mortality after small group harvesting in New Zealand old-growth *Nothofagus* forests. *Canadian Journal of Forest Research* 35: 1571- 1580.

Zhang, L., Peng, C. and Dang, Q. (2004). Individual-tree basal area growth models for jack pine and black spruce in northern Ontario. *Forestry Chronic* 80 (3): 366-374. - doi: 10.5558/tfc80366-3

Zhang, Y., Han, C., Reich, Y.H. and Peter B. (2012). Forest productivity increases with evenness, species richness and trait variation: a global meta-analysis. *Journal of Ecology*, 100 (3), 742–749. <https://doi.org/10.1111/j.1365-2745.2011.01944.x>.



Annexes

Annex 1: Descriptive statistics of Species by diameter class

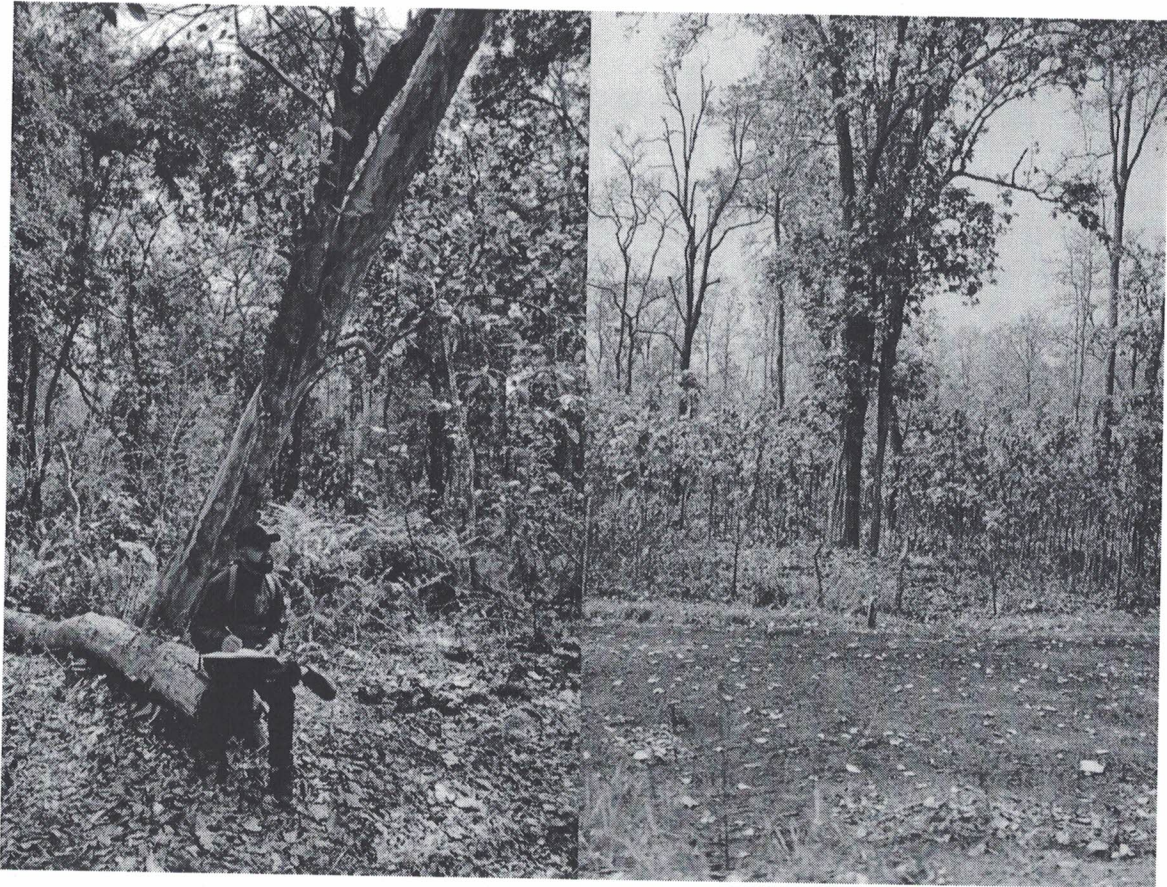
Species	DB H Class	Count		Mean		SD		Min		Max		Median	
		dbh 1	dbh 2	dbh1	dbh2	dbh 1	dbh 2	dbh 1	dbh 2	dbh 1	dbh 2	dbh1	dbh2
Sal	1	27		29.92		0		29.9 2		29.9 2		29.92	
Sal	2	229	133	34.94	36.15	2.86	2.44	30	30.2 4	39.8	39.8	34.7	36.61
Sal	3	239	201	45.36	45.19	2.84	2.91	40.1	40	49.9 8	49.9 8	45.5	45.2
Sal	4	311	262	55.4	55.23	2.85	3.03	50	50	59.9	59.9	55.7	55.2
Sal	5	234	320	64.61	64.51	2.78	2.83	60	60	69.7	69.9	64.3	64.2
Sal	6	186	217	74.46	74.49	3.1	2.76	70	70	79.9	79.9	74.2	74.6
Sal	7	101	143	84.52	83.99	3.06	2.73	80	80	89.8	89.7 7	84.7	84
Sal	8	40	73	94.96	93.95	3.1	2.78	90	90	99	99.6	94.25	94
Sal	9	18	26	104.9 9	103.8 1	4.01	2.81	100. 3	100	109. 9	109	105.3 7	104
Sal	10	7	14	114.3 7	113.8 4	3.91	2.57	110	110	119. 4	117	114.3	114.4 5
Sal	11	10	13	132.5 3	133.2 9	11.1 2	11.3 8	120. 4	120	157. 3	160	130.9 4	133.8
Asna	1	3		29.26		1.15		27.9 2		29.9 2		29.92	
Asna	2	37	28	35.33	35.5	2.99	2.61	30.2 4	30.2 4	39.7 9	39.4 7	35.65	35.17
Asna	3	34	32	45.13	44.28	3.19	2.69	40.4 3	40.1 1	49.7	49.5	44.58	43.8
Asna	4	44	40	54.79	54.93	2.91	2.61	50	50.2 9	59.9	59	54.1	55.55
Asna	5	48	49	64.14	64.88	2.91	2.48	60	60	69.4	69.9	63.85	64.9
Asna	6	26	30	74.33	73.81	3.37	2.59	70	70.1	78.7	79.9	74.1	73.2
Asna	7	31	33	84.08	84.31	3.04	2.92	80	80	88.2	89.6	85	84
Asna	8	16	22	94.34	93.77	2.97	2.59	90	90	99	99	94.15	93.3
Asna	9	7	9	103.6 4	104.8 3	2.17	2.5	102	100. 9	108	109. 2	103	104.8
Asna	10	5	8	111.8	114.0 3	2.39	3.11	110	110	116	119. 2	111	114.7 5
Asna	11	4	4	133	135.1 8	23.3 4	22.5 9	121	122. 1	168	169	121.5	124.8
Jingar	2	35	15	36.99	37.96	2.37	1.37	30.6	35	39.8	39.5	37.56	38
Jingar	3	37	42	44.55	44.09	3.05	2.79	40.1	40	49.7	49.9 8	43.9	44
Jingar	4	35	37	54.01	54.14	3.01	2.62	50.6	50	59.9	59	52.52	54
Jingar	5	10	19	64.4	64.04	3.1	2.97	60.8	60	68.5	69	65	63
Jingar	6	1	5	70.1	72.38	NA	1.68	70.1	70	70.1	74	70.1	72.1

Jingar	7	1	0	86.6		NA		86.6		86.6		86.6	
Jingar	8	0	1		94				94		94		94
Jamun	2	17	12	34.08	35.08	2.63	2.43	30.2 4	30.8 8	38.9	38.7	33.42	35.01
Jamun	3	19	19	44.37	45.23	2.63	2.45	40.1	40	49	48.7	44.3	46
Jamun	4	18	16	55.19	55.62	2.47	2.43	51.9	50	59.9	59.6	54.3	55.6
Jamun	5	9	12	64.66	64.1	3.05	2.91	61.5	61	68.8	69	65	64
Jamun	6	4	7	75.9	74.03	2.62	3.03	72.6	70	79	78.9	76	74
Jamun	7	4	3	81	85.57	1.17	3.25	80	83.4	82.2	89.3	80.9	84
Jamun	8	2	2	95.65	92.4	3.32	2.26	93.3	90.8	98	94	95.65	92.4
Jamun	9		2		105.5		4.95		102		109		105.5
Barro	1	3		29.92		0		29.9 2		29.9 2		29.92	
Barro	2	38	29	34.44	35.06	3.01	3.26	30.2 4	30.5 6	39.5	39.3	34.55	35.01
Barro	3	17	23	44.01	44.08	3	2.79	40.1	40	48.7	49	43.6	44
Barro	4	18	19	53.94	55.72	2.83	2	50	50	59.2	58.9	53.8	56
Barro	5	6	9	63.45	64.09	4.08	2.6	60	60.3	69	68.3	61.75	63
Barro	6	2	2	76.5	74.42	3.54	3.51	74	71.9 4	79	76.9	76.5	74.42
Barro	7	1	3	85	83.4	NA	2.79	85	80.3	85	85.7	85	84.2
Barro	8	1	1	92	92.5	NA	NA	92	92.5	92	92.5	92	92.5
Mixed species	1	6		27.78		3.58		21.3 7		29.9 2		29.92	
Mixed species	2	224	164	34.56	35.36	2.97	2.65	30	30	39.8	39.9	34.4	35
Mixed species	3	116	141	44.51	44.12	2.76	2.82	40	40	49.9 8	49.8	44.6	44
Mixed species	4	75	99	54.43	54.61	2.85	2.96	50	50	59.9	59.9	54.11	54.75
Mixed species	5	35	41	64.61	64.82	2.46	3.13	60	60	69.4	69.5	65	64.9
Mixed species	6	19	26	73.31	73.43	3.7	2.92	70	70	79.9	79	71.7	72
Mixed species	7	5	7	84.25	82.99	3.39	2.08	80	80	87.9	85.5	83	83
Mixed species	8	8	6	93.64	94.63	3.84	2.77	90	90	99	97.9	92.7	95.45
Mixed species	9	3	7	101.7 9	103.5	0.75	2.44	101	100	102. 5	106. 5	101.8 6	103.2
Mixed species	10	3	2	115.3 3	118.3 5	3.79	2.19	111	116. 8	118	119. 9	117	118.3 5
Mixed species	11	3	4	131.3 7	131.4 3	13.9 7	12.7 7	120. 1	122. 5	147	150. 1	127	126.5 5

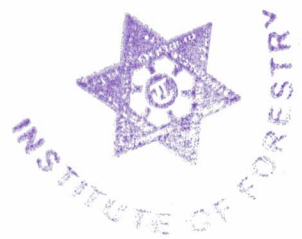
Annex 2: Field Photos

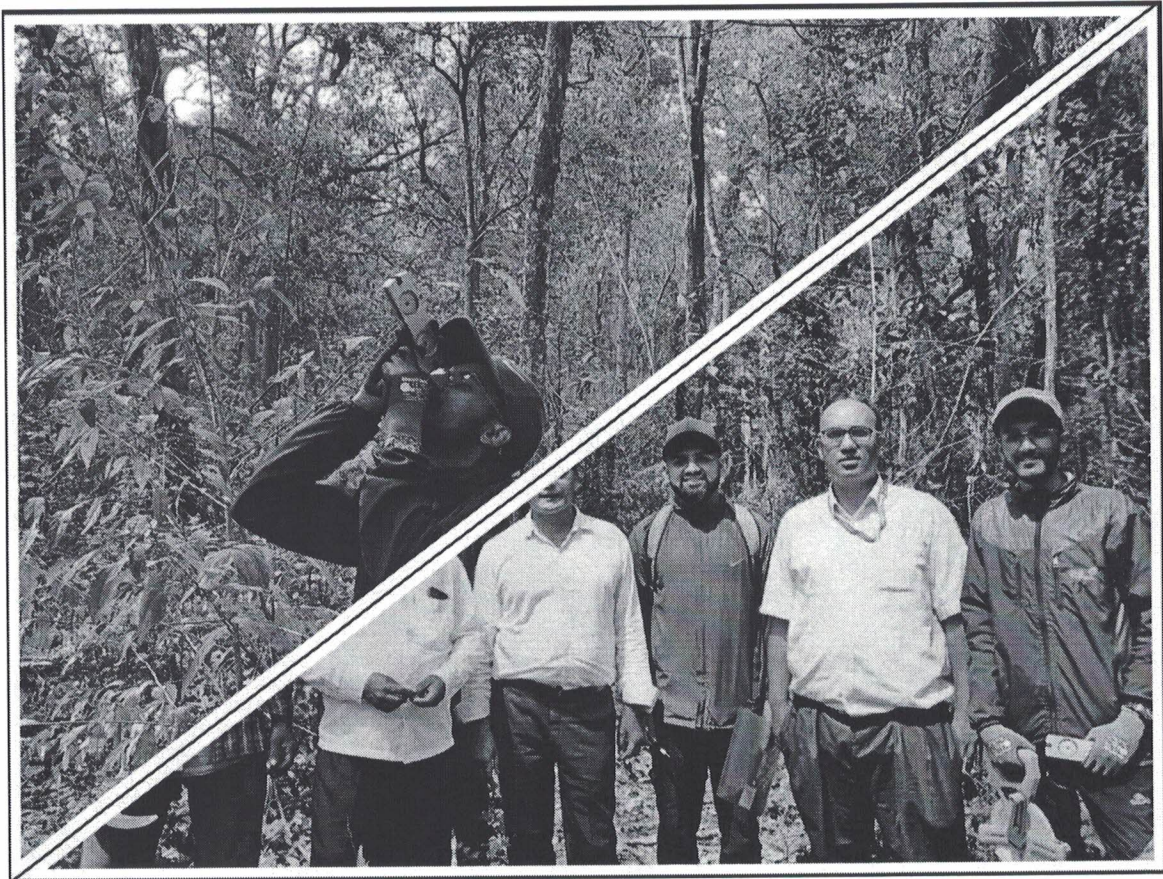


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Annex 3: Study Team

- | | |
|---|-------------|
| 1. Assoc. Prof. Dr. Bishnu Prasad Devkota | Team Leader |
| 2. Prof. Dr. Rajesh Kumar Rai | Team Member |
| 3. Assoc. Prof. Mr. Vijay Kumar Yadav | Team Member |
| 4. Assist. Prof. Dr. Dhruva Bijay GC | Team Member |



A handwritten signature in black ink, appearing to be "B. C.", is written below the logo.