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Survivability and Growth Performance of Sal (*Shorea robusta* C.F. Gaertn) with Compatible Associated and Naturally Grown Tropical Timber Tree Species in a Field Experiment at Madhupur Sal Forest, Bangladesh

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Abstract

This study aimed to develop a mixed plantation strategy, with Sal (*Shorea robusta*) as the primary tree species, along with four associated and two naturally grown tree species. Using a randomized complete block design (RCBD), the field experiment involved a control group (mono plantation) and three mixed plantation groups, each replicated four times, totaling 80 replicates (40 in 2019 and 40 in 2020). Survival rate, height and collar diameter growth of seedlings were recorded in both mono and mixed plots in July 2021. Statistical analyses, including one-way ANOVA on means from three replicate plots ($p<0.05$) and a Tukey HSD test, were conducted to assess differences between treatments. Significant differences in survival rates were found among mono plantations, with T_{Mono04} showing the highest survival rate (88% to 91%). However, there were no significant differences in survival rates among seedlings in mixed plantations. Notably, survival rates were lower in mono plantations compared to mixed plantations. Mono plantations showed significant differences in height growth across both 2019 and 2020 plots, with T_{Mono05} achieving the highest height growth (101.1 cm to 123.6 cm). Similarly, mixed plantations showed significant differences in height growth, with T_{Mixed7} displaying the most substantial growth (116.4 cm to 138.2 cm). Overall, mixed plantations showed greater height growth compared to mono plantations. Significant variations in collar diameter growth were noted in both the 2019 and 2020 mono plantation plots, with T_{Mono01} showing the highest growth (10.2 mm to 11.1 mm). Similarly, among mixed plantations, a significant difference in collar diameter growth was observed, with T_{Mixed4} exhibiting the highest growth (10.4 mm to 13.1 mm). Overall, mixed plantations showed higher collar diameter growth compared to mono plantations. The findings suggest that planting Sal trees alongside compatible associated and naturally grown tree species in the Sal forests is preferable over establishing mono plantations.

Key Words: associated species, mono plantation, mixed plantation, naturally grown species, *Shorea robusta*

Introduction

Sal (*Shorea robusta* C.F. Gaertn; Dipterocarpaceae family) is a large deciduous timber tree species that can reach a height of up to 50 m (average 18-32 m tall) with a straight cylindrical bole and a diameter of 3-5 m (Chitale and

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Behera 2012; Swaminathan and Kochhar 2019). Sal is native to tropical moist deciduous forests in the Indian subcontinent, including countries such as India, Bangladesh, Nepal, Bhutan, Myanmar, and Tibet, as well as across the Himalayan regions (Plants of the World Online 2022). In Bangladesh, Sal forests are primarily found in plain land areas, particularly in the central, eastern, and northern regions (Alam et al. 2008; Rahman et al. 2010). Plain land Sal forest covers an area of 46,338 hectares, which constitutes 2.46% of the total forest area and 8.7% of the country's land (GoB 2019). Sal is a highly valuable timber-yielding tree species, ranking after Teak (*Tectona grandis*), as its wood is renowned for its strength, durability, and fire-resistance (Swaminathan and Kochhar 2019). Timber is widely used for various construction purposes, including house building, electrical and telephone poles, boat construction, furniture, bullock-cart wheels, railway sleeper, and other carpentry works (Swaminathan and Kochhar 2019; Rahman 2021). This multipurpose tree is of great significance from both economic and environmental perspectives in South and Southeast Asia. Sal is the dominant tree species in moist deciduous forests and is often found growing alongside other valuable associated timber tree species in Bangladesh (Basak and Alam 2016; Rahman et al. 2019).

Sal forest is facing a serious threat due to continued forest clearing, introduction of fast-growing exotic tree species and habitat alteration resulting from increased population in central and northern regions, with limited alternatives for employment opportunities outside of forests (Alam et al. 2008; Rahman et al. 2009; Rahman et al. 2010; Roy et al. 2012; Rahman et al. 2019). Over the decades, the Sal forest has been identified as the most affected forest in the country, with reduced extent, tree density, and stand quality (Rahman et al. 2017). Furthermore, Deb et al. (2017) predicts that suitable climate space for Sal is expected to decline by 24% and 34% by 2070 under RCP4.5 and RCP8.5 scenarios, respectively. This underscores the urgent need for conservation and sustainable management of the Sal forest to safeguard this valuable natural resource for future generations.

Plantation forestry is a unique type of forest land use e.g., having one or two species, even age class, and regular spacing as defined by the Food and Agriculture Organization of the United Nations (FAO) (FAO 2018). Despite accounting for only 3% of the global forest area, plantation forests cover 11% of the total forest area. Remarkably, they likely supplied over 33% (654 out of 1984 million m^3) of the global industrial roundwood demand in 2020 (Mishra et al. 2021). In 2020, there were 293 million hectares of plantation forests worldwide, with 131 million hectares managed as planted forests for timber, and 162 million hectares classified as other planted forests (FAO 2020). Plantations have the potential to significantly impact soil fertility, with variations observed between different types of plantations, including those with native or exotic species, and nitrogen-fixing or non-nitrogen-fixing species (Singh et al. 2002; Bauhus et al. 2010; Rahman et al. 2012; Rahman and Bahauddin 2018).

Plantations have been rapidly expanded in response to deforestation and increasing wood demand, often replacing natural forests on disturbed and degraded soils (Liu et al. 2018; Hua et al. 2018). The expansion of plantations has raised questions about the availability of high-quality planting materials for various types of plantations, underscoring the importance of further research in this field. For instance, mixed-species plantation stands of valuable indigenous species have been found to provide diverse products and improve carbon storage in litter, soil, and ecosystems (He et al. 2013), making them a promising silvicultural alternative to large-scale monoculture plantations for climate change mitigation, facilitated by the sequestration of atmospheric carbon dioxide (Kanowski and Catterall 2010). However, above mentioned studies also have highlighted the increasing interest in mixed-species plantations worldwide as a response to resource scarcity and the negative effects of climate change.

Sal trees are known to regenerate through two main methods: seed origin and coppicing. Additionally, sprouting from root suckers is a prevalent mode of regeneration. Interestingly, both coppice and seed origin result in fertile seeds, and there is no discernible difference in the vigor of the resulting seedlings (Gautam and Devoe 2006; Rahman et al. 2019). In Bangladesh, Sal forests are often interplanted with associated tree species such as *Albizia procera, Artocarpus chama, Gmelia arborea, Phylenthus embelica, Butea frondosa, Cassia fistula, Adina codifolia,* and *Lagerstroemea parviflora.* In order to protect and conserve the remaining

Table 1. Botanical description of tree species in Bangladesh studied in the experiment

Local and scientific name	Family	Description	Conservation status
Sal (*Shorea robusta* C.F. Gaertn)	Dipterocarpaceae	- Large sub-deciduous native tree species, heights of 30-35 m tall, and a trunk diameter of up to 2-2.5 m - Simple and large leathery leaves - It has small yellowish flowers, and fruits are brown colored nut with 5 unequal linear wings - Timber is heavy, durable and useful for making furniture, railway sleeper, boat, pole, etc. - The tree is propagated by fresh seeds, and newly grown seedlings those grown from the base of the tree	Least concern (Ahmed et al. 2008b)
Lohakat (*Xylia xylocarpa* Roxb. Taub.)	Fabaceae	- This is a large-sized native deciduous tree, attaining a height of 40 m and its trunk diameter can be up to 60 cm - Leaves are compound, opposite, shiny - Flowers are small, yellowish and scented - Fruits are pods, long, brownish with 6-10-seeded - Wood is very hard, heavy and durable which is useful for making furniture, railway sleeper, etc. - The tree is propagated by seeds	Least concern (Ahmed et al. 2009a)
Civit (*Swintonia floribunda* Griffith)	Anacardiaceae	- This is a native evergreen tree, usually grows 30-45 m tall. The trunk diameter can be 50-90 cm - Leaves crowded towards the end of the branches, lanceolate - Bisexual flowers in pale yellow color - Fruits a drupe, unripe fruit sessile, purplish, have wing-shaped petals - Timber is moderately heavy and hard but not durable Mostly used for light carpentry and furniture, boxes, blockboard, plywood, etc. - The tree is propagated by seeds	Vulnerable (Ahmed et al. 2008a)
Chapalish (*Artocarpus chama* Buch-Ham)	Moraceae	- Perennial large-sized native deciduous tree, attaining a height of 30 m - Leaves are simple, alternate hairy, and petiolate - Fruit is exactly like Jackfruit, but much smaller and rounder in size. Ripen fruit is edible, tasty and eaten by wildlife (elephants and monkeys) and human - Timber is durable, used for furniture making, railway sleeper, etc. - The tree is propagated by seeds	Not evaluated but seems rare (Ahmed et al. 2009b)
Simul (*Bombax ceiba* L.)	Bombacaceae	- This is a large sized, fast growing, deciduous native tree species, height 30-60 m tall - Leaves are large, digitately compound, glabrous, long petiole - 5 petal complete flowers are red in color on the defoliate branch - Fruits are like oblong capsule and seeds are embedded with cotton - Silk cotton is widely used for stuffing mattresses and pillows - The wood is soft and used to make boxes and sticks, and as fuelwood - The tree is propagated by seeds	Least concern (Ahmed et al. 2008b)

Table 1. Continued

Local and scientific name	Family	Description	Conservation status
Sil Koroi (*Albizia procera* Roxb. Benth.)	Mimosaceae	- It is a fast-growing, large-sized deciduous tree, attaining a height of 15-20 m - Leaves bipinnate with a large gland on the base of petiole, ovate, oblong - Flowers are very fragrant, greenish white, heads globose, containing many flowers - The fruit is a legume, contains 6-12 seeds - Timber is durable, used for furniture making - The tree is propagated by seeds	Least concern (Ahmed et al. 2009b)
Udal (*Sterculia villosa* Roxb.)	Malvaceae	- A medium-sized deciduous native tree species, height up to 10 m tall - Leaves are simple, alternate, long petioled, and large ovate-oblong - Flowers are orange-yellow, polygamous - Fruits are long, curved, brown, tomentose - The plant is used to make tea boxes and lightweight packing cases, and as fuelwood - The tree is propagated by seeds	Least concern (Ahmed et al. 2009b)

Source: Ahmed et al. (2008a, b); Ahmed et al. (2009a, b); Pasha and Uddin (2013).

Sal forests of Bangladesh, it is crucial to improve silvicultural systems to promote effective regeneration and ensure sustainable management (Rahman et al. 2010). Therefore, enriching the Sal forests through mixed field experiments of Sal with its associated species and other naturally grown or site-suitable tree species is imperative to enhance the diversity and resilience of the Sal forests. The study aims to develop a mixed plantation combination of Sal tree with four associated tree species namely, *Artocarpus chama* Buch-Ham (Chapalish), *Bombax ceiba* L. (Shimul), *Albizia procera* Roxb. (Sil Koroi), and *Sterculia villosa* Roxb. (Udal), along with two naturally grown tree species namely, *Xylia xylocarpa* Roxb. Taub. (Lohakath) and *Swintonia floribunda* Griffith (Civit) to restore and enrich degraded Sal forests in central Bangladesh.

Materials and Methods

Field experimental site

The field experiment was conducted at the Charaljani Silviculture Research Station of the Bangladesh Forest Research Institute, which is located in the Madhupur Upazila (subdistrict) under the Tangail district in the central region of Bangladesh. This research site is in close proximity to the Madhupur Sal Forest. It has a tropical monsoon climate characterized by hot and humid summers, as well as cool and dry winters (Rahman et al. 2009; Roy et al. 2012). The monsoon season typically occurs from June to October, with rainfall ranging from 2,000 to 2,300 mm. The peak of rainfall usually takes place from May to September, with occasional dry spells in January to April. The winter season, with a minimum temperature of 18.5°C, spans from mid-November to February (Rahman 2003). The experimental nursery is located at approximately 24°37’N latitude and 90°04’E longitude, at an altitude of 20 m.

The area is geographically characterized by flat to very gently sloping terrain. The soil in this region is a mix of yellowish-red sandy clay, which becomes very hard during the dry season and becomes loose during the rainy season (Roy et al. 2012). In the rainy season, the soil is highly fertile and suitable for plant growth (Alam 1995). The soil is deep with good drainage, ranging from clay loam (0-15 cm) to clay (below), and slightly acidic to almost neutral, with a pH range of 5.5-6.0 for topsoil and 5.0-5.5 for subsoil (Alam 1995; Nishat et al. 2002). The soil is not stony, with a low content of organic matter, less than 2.5% within 15 cm depth. The soil color is brown, derived from plio-Pleistocene sediments (Rashid 2001).

Seedling raising

The field experiment was conducted in June and July of both 2019 and 2020. To produce seedling, mature seeds from each tree species were thoughtfully gathered from meticulously selected mother trees situated at various locations within the Madhupur Sal Forest. Seedlings of Sal and other associated and naturally grown tree species were raised in polybags sized 15×17 cm, which were filled with a mixture of soil from various sites within the Madhupur Sal Forest. This soil was carefully air-dried and mixed with cow dung in a 3:1 ratio. Regular weeding, watering, sorting for grading, and rearrangement for proper sunlight were carried out to maintain the seedlings in the nursery. One month before transplanting them into the experimental plots, seedling grading was conducted.

Experimental plot design

In addition to Sal trees, the present study also included six other timber tree species, namely *A. chama*, *B. ceiba, A. procera, S. villosa* (as associate tree species), *X. xylocarpa* and *S. floribunda* (as naturally grown tree species). Table 1 (Ahmed et al. 2008a; 2008b; 2009a; 2009b; Pasha and Uddin 2013) provides a detailed botanical description of each of these seven tree species.

One-year and two-year-old seedlings were used for the field experiment. The experimental plantation strategy followed a randomized complete block design (RCBD) with a total of 80 plots established over two years. Each year included a control group (mono plantation) and three treatment groups, each replicated four times. The experiment was conducted using a total of 80 replicates, with 40 replicates in 2019 and 40 replicates in 2020 (Table 2). Except for the change in timber tree species, all treatments remained the same for the experiments in 2019 and 2020. Apart from the change in the association of timber tree species with Sal, all other applied treatments remained the same for the experiments conducted in both 2019 and 2020.

The experimental site was cleared through slashing every year from April to May in preparation for the experiment that took place from June to July in the same year. Each replication plot had a size of 14 m×14 m and contained 32 seedlings for mono plantation (control) and 48 seedlings for mixed plantations (treatment) in a 4:3 ratio of Sal to selected species at 2 m×2 m spacing. In the mixed plantations under consideration, 24 seedlings were strategically planted, with Sal as the main species, associated with three other valuable timber tree species. Simultaneously, another set of 24 seedlings was carefully planted, with Sal as an as-

Table 2. Overview of plantation treatments employed in the study, including mono and mixed treatment plantation plots

Mono plantation plots	Replicates	Mixed plantation plots	Replicates
2019 plantation			
T_{Mono00}=Sal (*Shorea robusta*)	4	-	-
T_{Mono01}=Shimul (*Bombax ceiba*)	4	T_{Mixed1}=Sal+Shimul	4
T_{Mono02}=Chapalish (*Artocarpus chama*)	4	T_{Mixed2}=Sal+Chapalish	4
T_{Mono03}=Udal (*Sterculia villosa*)	4	T_{Mixed3}=Sal+Udal	4
		T_{Mixed4}=Shimul+Sal	4
		T_{Mixed5}=Chapalish+Sal	4
		T_{Mixed6}=Udal+Sal	4
2020 plantation			
T_{Mono04}=Sal (*Shorea robusta*)	4	-	-
T_{Mono05}=Sil Koroi (*Albizia procera*)	4	T_{Mixed7}=Sal+Sil Koroi	4
T_{Mono06}=Lohakath (*Xylia xylocarpa*)	4	T_{Mixed8}=Sal+Lohakath	4
T_{Mono07}=Civit (*Swintonia floribunda*)	4	T_{Mixed9}=Sal+Civit	4
		$T_{Mixed10}$=Sil Koroi+Sal	4
		$T_{Mixed11}$=Lohakath+Sal	4
		$T_{Mixed12}$=Civit+Sal	4

sociate species, intermingling with an additional three timber tree species. Four lines were used for Sal and three lines for the selected species, with single-line alternation applied in the mixed plantation. The size of each pit was 30 cm×30 cm. In July 2021, data was collected on the seedlings, which included the survival rate, height, and collar diameter of both the two-year-old and one-year-old seedlings of Sal and other species. The data was collected from both mono and mixed field experimental plots.

Statistical analysis

Average survival rate (expressed in %), height growth (in cm), and collar diameter (in mm) were compared among mono and mixed plantation plots of the studied tree species. One-way Analysis of Variance (ANOVA) was conducted, and tests for means were performed at a significance level of $p<0.05$ using the means of each variable from each of the three replicate plots. After ANOVA, Tukey's Honest Significant Difference (Tukey HSD) test was conducted to evaluate the actual difference between the means of survival rate, height growth and collar diameter growth by treatments (expressed in T) of the seedlings for mono and mixed plantation plots for both 2019 and 2020 planting seasons. The Tukey HSD test compares all possible pairs of group means and calculates the minimum difference needed for the means to be considered significantly different while controlling for the overall error rate. It helps to pinpoint specific pairs of tree species or treatments where significant differences exist in terms of survivability, height and collar diameter growths. All the data collected were statistically analyzed using R software (version 3.6.1).

Results

Findings from plantation treatments

The recorded data of survival rate and preliminary growth performance (e.g., height and collar diameter) of Sal mixed with naturally grown and associated tree species in the years 2019 and 2020 were combinedly shown in Figs. 1-6.

Field observations on seedling survivability in experimental plots

Statistically significant differences in seedling survivability (%) of mono plantation tree species were evident among the experimental plots, as indicated by a one-way ANOVA ($F=9.0$ and $Pr\ (>F)=1.95\times10^{-5***}$). The p-value is low ($p<0.001$), so it appears that the type of tree species used has a real impact on the survivability of seedlings. This trend was observed across both the 2019 and 2020 plantation plots, as illustrated in Fig. 1. T_{Mono04} (Sal 2020 plantation) demonstrated the highest survivability rate among seedlings, ranging from 88% to 91%. This was followed by T_{Mono06} (Lohakath) with a survivability range of 81.6% to 86%, and T_{Mono02} (Chapalish) with a range of 83.7% to 85.7%.

No statistically significant differences were observed in the seedling survivability percentages of mixed plantations, as confirmed by a one-way ANOVA ($F=11.8$, $Pr\ (>F)=$

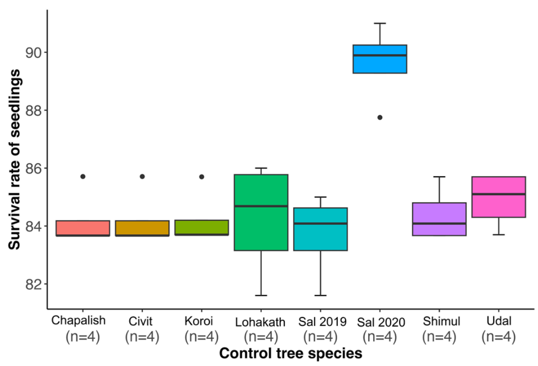

Fig. 1. Survival rate of each seedling from the control tree species used in the 2019 and 2020 plantation plots.

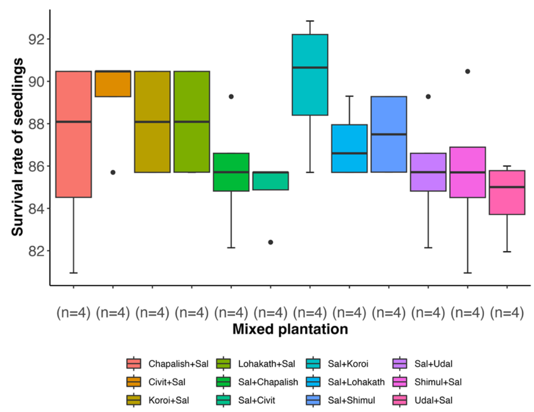

Fig. 2. Survival rate of each seedling from the mixed plantation tree species used in the 2019 and 2020 plantation plots.

0.194). This consistent trend was evident in both the 2019 and 2020 plantation plots, as depicted in Fig. 2. Within the mixed treatment plots, T_{Mixed7} (Sal+Sil Koroi) showcased the highest survivability rate, ranging from 85.7% to 92.9%. Meanwhile, T_{Mixed4} (Shimul+Sal), T_{Mixed5} (Chapalish+Sal), $T_{Mixed10}$ (Sil Koroi+Sal), $T_{Mixed11}$ (Lohakath+Sal), and $T_{Mixed12}$ (Civit+Sal) collectively demonstrated an average survivability rate of 90.5%. Figs. 1, 2 also illustrate that the survivability rates were notably lower in the mono plantation plots compared to the mixed plantation plots. Additionally, the 2020 plantations exhibited higher survivability rates for both mono and mixed plantations in contrast to those from 2019.

Field observations on seedling height growth in experimental plots

The mono plantation experimental plots showed a statistically significant difference in the height growth (measured in cm) of the studied species across both the 2019 and 2020 plantation plots, as illustrated in Fig. 3 and confirmed by a one-way ANOVA (F=77.9 and Pr (>F)=$5.96\times10^{-15***}$). The low p-value ($p<0.001$) suggests a substantial impact of the tree species on the height growth of seedlings. T_{Mono05} (Sil Koroi) displayed the highest height growth between the seedlings, ranging from 101.1 cm to 123.6 cm. Subsequently, T_{Mono01} (Shimul) showed a height range of 87.9 cm to 93.8 cm, and T_{Mono04} (Sal 2020 plantation) with a height range of 67.8 cm to 77.6 cm.

A statistically significant difference in height growth (measured in cm) was observed for the mixed experimental plantation plots, as shown in Fig. 4 with a one-way ANOVA (F=65.0 and Pr (>F)=$2\times10^{-16***}$). The low p-value ($p<0.001$) strongly suggests that the combination of tree species significantly influences the height growth of seedlings. The T_{Mixed7} (Sil Koroi+Sal) exhibited the most substantial height growth, ranging from 116.4 cm to 138.2 cm. In comparison, T_{Mixed4} (Shimul+Sal) showed a height range of 92 cm to 104.2 cm, and T_{Mixed9} (Sal+Civit) displayed a height range of 67.7 cm to 83.1 cm.

Figs. 3, 4 highlight that mixed plantations exhibit greater height growth compared to mono plantations. Particularly, species like T_{Mono01} (Shimul) and T_{Mono05} (Sil Koroi) display significantly superior height growth when compared to other species. Moreover, the plantation plots from 2020 demonstrated greater height growth in comparison to those planted in 2019.

Field observations on seedling collar diameter growth in experimental plots

Statistically significant variations in collar diameter growth (measured in mm) were observed among the studied species in the mono plantation experimental plots for both the 2019 and 2020 plantation plots. This discrepancy is depicted in Fig. 5 and was validated through a one-way ANOVA (F=68.8 and Pr (>F)=$2.43\times10^{-14***}$). The considerably low p-value ($p<0.001$) strongly indicates that the number of tree species significantly impacts the collar diameter growth of seedlings. T_{Mono01} (Shimul) exhibited the highest collar diameter growth between the seedlings,

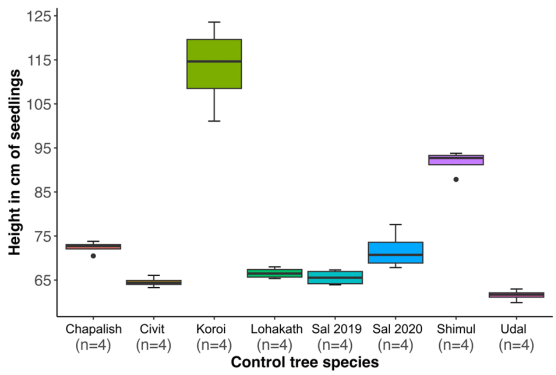

Fig. 3. Height growth (in cm) of each seedling from the control tree species used in the 2019 and 2020 plantation plots.

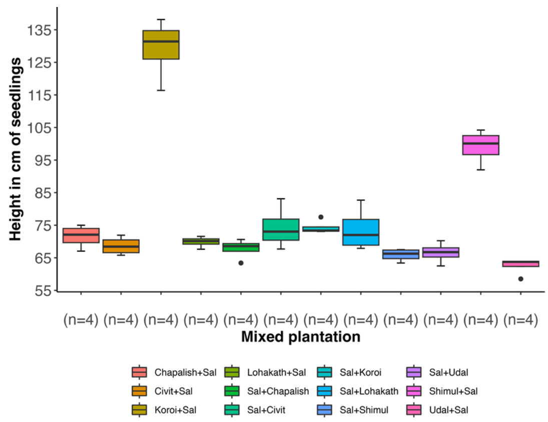

Fig. 4. Height growth (in cm) of each seedling from the mixed plantation tree species used in the 2019 and 2020 plantation plots.

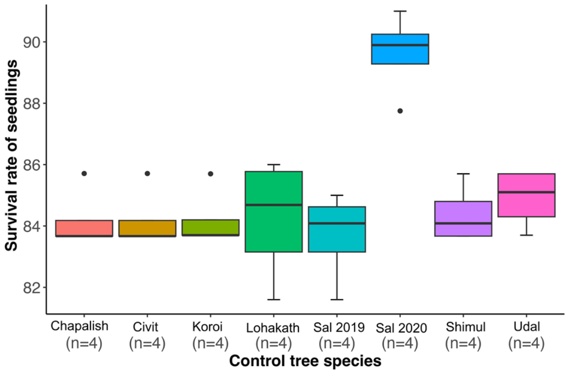

Fig. 5. Collar diameter growth (in mm) of each seedling from the control tree species used in the 2019 and 2020 plantation plots.

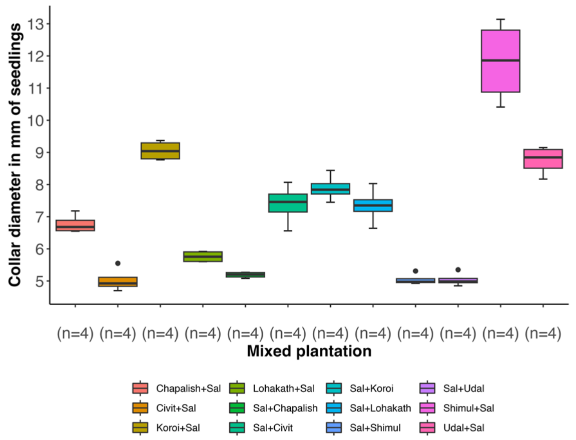

Fig. 6. Collar diameter growth (in mm) of each seedling from the mixed plantation tree species used in the 2019 and 2020 plantation plots.

ranging between 10.2 mm and 11.1 mm. Following this, T_{Mono05} (Sil Koroi) demonstrated a collar diameter range of 7.7 mm to 9.7 mm, while T_{Mono03} (Udal) displayed a collar diameter range of 8.1 mm to 9 mm.

A statistically significant difference in collar diameter growth (measured in mm) was evident among the mixed plantation plots, as shown in Fig. 6 using a one-way ANOVA ($F=64.7$ and $Pr\ (>F)=2\times10^{-16***}$). The notably low p-value ($p<0.001$) strongly underscores the substantial impact of the tree species combination on the collar diameter growth of seedlings. T_{Mixed4} (Shimul+Sal) displayed the highest collar diameter growth, ranging from 10.4 mm to 13.1 mm. In contrast, $T_{Mixed10}$ (Sil Koroi+Sal) exhibited a collar diameter range of 8.8 mm to 9.4 mm, while T_{Mixed6} (Udal+Sal) demonstrated a collar diameter range of 8.2 mm to 9.2 mm.

Figs. 5, 6 emphasize the heightened collar diameter growth in mixed plantations compared to mono plantations. Specifically, species such as T_{Mono01} (Shimul), T_{Mono03} (Udal) and T_{Mono05} (Sil Koroi) showcase notably superior collar diameter growth in contrast to other species. Additionally, the plantation plots from 2019 and 2020 exhibited less variability in collar diameter measurements.

Tukey's Honest Significant Difference test results

Table 3 presents the outcomes of the Tukey HSD test concerning the survival rate, height growth, and collar diameter growth among seedlings in monoculture and mixed plantation plots for both the 2019 and 2020 planting seasons. Regarding seedling survivability, a significant difference was observed solely between T_{Mono00} (Sal 2019 plantation) and T_{Mixed7} (Sal+Sil Koroi), exhibiting an adjusted p-value of 0.0420027. Conversely, no statistically significant variance was detected in the mean survival rates among other pairs of tree species.

For height growth, several comparisons stand out with adjusted p-values of 0.0000000, indicating substantial differences between pairs (one-way ANOVA ($df=19$, $F=65.8$, $Pr\ (>F)=<2\times10^{-16***}$)), such as: T_{Mono04} (Sal 2020 plantation) and T_{Mono05} (Sil Koroi), T_{Mono04} (Sal 2020 plantation) and $T_{Mixed10}$ (Sil Koroi+Sal), T_{Mixed7} (Sal+Sil Koroi) and T_{Mono05} (Sil Koroi), T_{Mixed7} (Sal+Koroi) and $T_{Mixed10}$ (Sil Koroi+Sal), $T_{Mixed10}$ (Sil Koroi+Sal) and T_{Mono05} (Sil Koroi), T_{Mono03} (Udal) and T_{Mono05} (Sil Koroi), T_{Mono03} (Udal) and T_{Mono01} (Shimul), T_{Mixed6} (Udal+Sal) and T_{Mono05} (Sil Koroi), T_{Mono03} (Udal) and T_{Mixed7} (Sal+Sil Koroi), T_{Mono03} (Udal) and T_{Mixed8} (Sal+Lohakath), T_{Mono03} (Udal) and $T_{Mixed10}$ (Sil Koroi+Sal), T_{Mixed6} (Udal+Sal) and $T_{Mixed10}$ (Sil Koroi+Sal), T_{Mixed6} (Udal+Sal) and T_{Mixed7} (Sal+Sil Koroi). These results underscore significant variations in height growth between these specific pairs.

In terms of collar diameter growth, every species exhibited significant distinct comparisons, with adjusted p-values of 0.0000000. This suggests significant disparities among the pairs (one way ANOVA ($df=19$, $F=63.8$, $Pr\ (>F)=<2\times10^{-16***}$)), including: T_{Mono07} (Civit) and T_{Mono02} (Chapalish), T_{Mono03} (Udal) and T_{Mono07} (Civit), T_{Mono03} (Udal) and T_{Mono00} (Sal 2019 plantation), $T_{Mixed12}$

Table 3. Tukey's Honest Significant Difference test results for the survival rate, height growth and collar diameter growth of the seedlings of mono and mixed treatment plantation plots

Plantation plots	Adjusted p-value		Plantation plots	Adjusted p-value	
	Height	Collar diameter		Height	Collar diameter
Chapalish+Sal-Chapalish		0.0020775	Shimul-Civit	0.0000000	0.0000000
Civit-Chapalish		0.0000000	Shimul-Koroi	0.0000006	0.0000871
Civit+Sal-Chapalish		0.0000000	Shimul-Lohakath	0.0000000	0.0000000
Civit-Chapalish+Sal		0.0046293	Shimul-Sal2019	0.0000000	0.0000000
Civit+Sal-Chapalish+Sal		0.0010269	Shimul-Sal2020	0.0000049	0.0000000
Sal2019-Sal+Koroi		0.0000000	Shimul-Chapalish		0.0000039
Sal2019-Koroi+Sal	0.0000000	0.0000000	Shimul+Sal-Chapalish	0.0000000	0.0000000
Sal2019-Sal+Civit		0.0000024	Shimul+Sal-Civit	0.0000000	0.0000000
Sal2019-Koroi	0.0000000	0.0000000	Shimul+Sal-Koroi	0.0034436	0.0000000
Sal2019-Chapalish		0.0000000	Shimul+Sal-Lohakath	0.0000000	0.0000000
Sal2019-Chapalish+Sal		0.0014818	Shimul+Sal-Sal2019	0.0000000	0.0000000
Sal2019-Sal+Lohakath		0.0000039	Shimul+Sal-Sal2020	0.0000000	0.0000000
Sal2020-Sal+Shimul		0.0000001	Shimul-Chapalish+Sal	0.0000040	0.0000000
Sal2020-Sal+Udal		0.0000001	Shimul-Civit+Sal	0.0000001	0.0000000
Sal2020-Sal2019		0.0000002	Shimul-Koroi+Sal	0.0000000	0.0021279
Sal2020-Civit		0.0000006	Shimul-Lohakath+Sal	0.0000005	0.0000000
Sal2020-Koroi	0.0000000		Shimul-Sal+Chapalish	0.0000000	0.0000000
Sal2020-Koroi+Sal	0.0000000	0.0195593	Shimul-Sal+Civit	0.0000994	0.0000000
Sal2020-Lohakath		0.0376979	Shimul-Sal+Koroi	0.0001092	0.0000000
Sal2020-Lohakath+Sal		0.0003009	Shimul-Sal+Lohakath	0.0000502	0.0000000
Sal2020-Sal+Chapalish		0.0000007	Shimul-Sal+Shimul	0.0000000	0.0000000
Sal+Chapalish-Koroi	0.0000000	0.0000000	Shimul-Sal+Udal	0.0000000	0.0000000
Sal+Chapalish-Koroi+Sal	0.0000000	0.0000000	Shimul+Sal-Chapalish+Sal	0.0000000	0.0000000
Sal+Chapalish-Chapalish		0.0000000	Shimul+Sal-Civit+Sal	0.0000000	0.0000000
Sal+Chapalish-Chapalish+Sal		0.0048483	Shimul+Sal-Koroi+Sal	0.0000000	0.0000000
Sal+Civit-Koroi	0.0000000	0.0369554	Shimul+Sal-Lohakath+Sal	0.0000000	0.0000000
Sal+Civit-Koroi+Sal	0.0000000	0.0022322	Shimul+Sal-Sal+Chapalish	0.0000000	0.0000000
Sal+Civit-Civit		0.0000088	Shimul+Sal-Sal+Civit	0.0000000	0.0000000
Sal+Civit-Civit+Sal		0.0000016	Shimul+Sal-Sal+Koroi	0.0000000	0.0000000
Sal+Civit-Lohakath+Sal		0.0031865	Shimul+Sal-Sal+Lohakath	0.0000000	0.0000000
Sal+Civit-Sal+Chapalish		0.0000093	Shimul+Sal-Sal+Shimul	0.0000000	0.0000000
Sal+Koroi-Koroi	0.0000000		Shimul+Sal-Sal+Udal	0.0000000	0.0000000
Sal+Koroi-Koroi+Sal	0.0000000		Udal-Koroi	0.0000000	
Sal+Koroi-Civit		0.0000000	Udal-Shimul	0.0000000	
Sal+Koroi-Civit+Sal		0.0000000	Udal-Civit		0.0000000
Sal+Koroi-Lohakath		0.0037552	Udal-Lohakath		0.0000028
Sal+Koroi-Lohakath+Sal		0.0000188	Udal-Sal2019		0.0000000
Sal+Koroi-Sal+Chapalish		0.0000000	Udal-Shimul		0.0000183
Sal+Lohakath-Koroi	0.0000000	0.0256554	Udal+Sal-Koroi	0.0000000	
Sal+Lohakath-Koroi+Sal	0.0000000	0.0014463	Udal+Sal-Shimul	0.0000000	0.0001019
Sal+Lohakath-Civit		0.0000144	Udal+Sal-Civit		0.0000000
Sal+Lohakath-Civit+Sal		0.0000026	Udal+Sal-Lohakath		0.0000005
Sal+Lohakath-Lohakath+Sal		0.0048483	Udal+Sal-Sal2019		0.0000000
Sal+Lohakath-Sal+Chapalish		0.0000151	Udal-Sal+Koroi	0.0179350	
Sal+Shimul-Koroi	0.0000000	0.0000000	Udal-Sal+Lohakath	0.0331357	

Table 3. Continued

Plantation plots	Adjusted p-value		Plantation plots	Adjusted p-value	
	Height	Collar diameter		Height	Collar diameter
Sal+Shimul-Koroi+Sal	0.0000000	0.0000000	Udal-Sal+Shimul		0.0000000
Sal+Shimul-Chapalish		0.0000000	Udal-Sal+Udal		0.0000000
Sal+Shimul-Chapalish+Sal		0.0012804	Udal-Sal+Chapalish		0.0000000
Sal+Shimul-Sal+Civit		0.0000020	Udal-Shimul+Sal	0.0000000	0.0000000
Sal+Shimul-Sal+Koroi		0.0000000	Udal-Chapalish+Sal		0.0005118
Sal+Shimul-Sal+Lohakath		0.0000033	Udal-Civit+Sal		0.0000000
Sal+Udal-Koroi	0.0000000	0.0000000	Udal-Lohakath+Sal		0.0000000
Sal+Udal-Koroi+Sal	0.0000000	0.0000000	Udal-Koroi+Sal	0.0000000	
Sal+Udal-Chapalish		0.0000000	Udal+Sal-Koroi+Sal	0.0000000	
Sal+Udal-Chapalish+Sal		0.0012193	Udal+Sal-Sal+Koroi	0.0420255	
Sal+Udal-Sal+Civit		0.0000019	Udal+Sal-Shimul+Sal	0.0000000	0.0000000
Sal+Udal-Sal+Koroi		0.0000000	Udal+Sal-Chapalish+Sal		0.0000967
Sal+Udal-Sal+Lohakath		0.0000032	Udal+Sal-Civit+Sal		0.0000000
Koroi-Civit+Sal	0.0000000	0.0000000	Udal+Sal-Lohakath+Sal		0.0000000
Koroi+Sal-Civit+Sal	0.0000000	0.0000000	Udal+Sal-Sal+Chapalish		0.0000000
Koroi-Chapalish	0.0000000		Udal+Sal-Sal+Civit		0.0327693
Koroi+Sal-Chapalish	0.0000000		Udal+Sal-Sal+Lohakath		0.0226535
Koroi-Chapalish+Sal	0.0000000	0.0001131	Udal+Sal-Sal+Shimul		0.0000000
Koroi+Sal-Chapalish+Sal	0.0000000	0.0000038	Udal+Sal-Sal+Udal		0.0000000
Koroi-Civit	0.0000000	0.0000000			
Koroi+Sal-Civit	0.0000000	0.0000000			
Koroi+Sal-Koroi	0.0006953				
Lohakath-Koroi	0.0000000	0.0000006			
Lohakath+Sal-Koroi	0.0000000	0.0000000			
Lohakath-Koroi+Sal	0.0000000	0.0000000			
Lohakath+Sal-Koroi+Sal	0.0000000	0.0000000			
Lohakath-Chapalish		0.0000132			
Lohakath+Sal-Chapalish		0.0000000			

Tukey multiple comparisons of means 95% family-wise confidence level; only significant differences are shown in the table.

(Civit+Sal) and T_{Mono02} (Chapalish), T_{Mono00} (Sal 2019 plantation) and T_{Mixed7} (Sal+Sil Koroi), T_{Mixed2} (Sal+Chapalish) and T_{Mono02} (Chapalish), T_{Mixed7} (Sal+Sil Koroi) and T_{Mono07} (Civit), T_{Mixed7} (Sal+Sil Koroi) and T_{Mixed12} (Civit+Sal), T_{Mixed7} (Sal+Sil Koroi) and T_{Mixed2} (Sal+Chapalish), T_{Mixed1} (Sal + Shimul) and T_{Mono02} (Chapalish), T_{Mixed1} (Sal+Shimul) and T_{Mixed7} (Sal+Sil Koroi), T_{Mixed3} (Sal+Udal) and T_{Mono02} (Chapalish), T_{Mixed3} (Sal+Udal) and T_{Mixed7} (Sal+Sil Koroi), T_{Mixed11} (Lohakath+Sal) and T_{Mono02} (Chapalish), T_{Mixed6} (Udal+Sal) and T_{Mono07} (Civit), T_{Mixed6} (Udal+Sal) and T_{Mono00} (Sal 2019 plantation), T_{Mono03} (Udal) and T_{Mixed1} (Sal+Shimul), T_{Mono03} (Udal) and T_{Mixed3} (Sal+Udal), T_{Mono03} (Udal) and T_{Mixed2} (Sal+Chapalish), T_{Mono03} (Udal) and T_{Mixed12} (Civit+Sal), T_{Mono03} (Udal) and T_{Mixed11} (Lohakath+Sal), T_{Mixed6} (Udal+Sal) and T_{Mixed12} (Civit+Sal), T_{Mixed6} (Udal+Sal) and T_{Mixed11} (Lohakath +Sal), T_{Mixed6} (Udal+Sal) and T_{Mixed2} (Sal+Chapalish), T_{Mixed6} (Udal+Sal) and T_{Mixed1} (Sal+Shimul), and T_{Mixed6} (Udal+Sal) and T_{Mixed3} (Sal+Udal).

Furthermore, certain species exhibit notable differences in both height and collar diameter growth, marked by adjusted p-values of 0.0000000. This indicates substantial variations among these pairs, encompassing: T_{Mono00} (Sal 2019 plantation) and T_{Mono05} (Sil Koroi), T_{Mono05} (Sil Koroi) and T_{Mono07} (Civit), T_{Mono01} (Shimul) and T_{Mono07}

(Civit), T_{Mono01} (Shimul) and T_{Mono00} (Sal 2019 plantation), T_{Mono03} (Udal) and T_{Mono07} (Civit), T_{Mono00} (Sal 2019 plantation) and $T_{Mixed10}$ (Sil Koroi+Sal), T_{Mixed2} (Sal+Chapalish) and T_{Mono05} (Sil Koroi), T_{Mixed2} (Sal+Chapalish) and $T_{Mixed10}$ (Sil Koroi+Sal), T_{Mixed1} (Sal+Shimul) and T_{Mono05} (Sil Koroi), T_{Mixed1} (Sal+Shimul) and $T_{Mixed10}$ (Sil Koroi+Sal), T_{Mixed3} (Sal+Udal) and T_{Mono05} (Sil Koroi), T_{Mixed3} (Sal+Udal) and $T_{Mixed10}$ (Sil Koroi+Sal), T_{Mono05} (Sil Koroi) and $T_{Mixed12}$ (Civit+Sal), $T_{Mixed10}$ (Sil Koroi+Sal) and $T_{Mixed12}$ (Civit+Sal), $T_{Mixed10}$ (Sil Koroi+Sal) and T_{Mono07} (Civit), T_{Mixed4} (Shimul+Sal) and T_{Mono02} (Chapalish), T_{Mixed4} (Shimul+Sal) and T_{Mono07} (Civit), and T_{Mono03} (Udal) and T_{Mixed4} (Shimul+Sal).

Discussion

In this study, to prevent soil degradation and restore soil fertility, we considered a mixed plantation strategy of associated and naturally grown or site-suitable tropical timber tree species to be planted alongside Sal tree species in the central region of Bangladesh. The study revealed significant differences in survivability and growth performance, particularly in the height growth and collar diameter growth, between Sal mono plantation and its mixed plantation plots, as well as between its associated and naturally grown species. However, with the exception of collar diameter of T_{Mono02} (Chapalish) and T_{Mono06} (Lohakath), no significant difference was observed between mono plantation and mixed plantation. The results also indicated that, in most cases, the survival rate, height growth and collar diameter growth of seedlings in mono plantation plots were lower compared to those in mixed plantation plots. Dutta and Hossain (2017) suggest that the reason for the better initial growth performance observed in mixed plots, as compared to mono plantations, could be attributed to the greater intra-specific competition among seedlings for resources in mono plantations than in mixed ones. Nguyen et al. (2015) further support the notion that mixed plantation can lead to greater productivity and financial benefits by reducing the impact of catastrophic loss resulting from poor performance, pest attacks, and a decline in economic value of any one tree species. This is because mixed plantation offers multiple products and hence, greater resilience to potential losses.

The field experimental results demonstrated that T_{Mono00} (Sal) tree, when planted with its associated and naturally grown tree species, exhibited better initial growth performance in mixed plots as compared to mono plots. The height growth of seedlings in mixed plots showed better performance than those in mono plots, except for T_{Mono02} (Chapalish), where the difference was not significant. The T_{Mixed1} (Sal+Shimul), T_{Mixed2} (Sal+Chapalish), T_{Mixed3} (Sal+Udal) and T_{Mixed7} (Sal+Sil Koroi) combination showed a better survival rate, height growth, and collar diameter growth for T_{Mono00} (Sal) seedlings. Several studies have demonstrated that mixed-species plantations exhibit higher productivity than mono plantations (Kanowski et al. 2005; Petit and Montagnini 2006; Richards et al. 2010; Kanowski and Catterall 2010; Zhang et al. 2012; Pretzsch and Schütze 2016). For instance, Forrester et al. (2006) highlighted that the mixing of eucalyptus with nitrogen-fixing species resulted in increased productivity and nutrient cycling rates, with better outcomes than monoculture.

Our field experiment has revealed that mixed plantations can have a significant impact on growth performance, thereby supporting the notion that mixed-species plantations may have either positive or negative effects on tree growth (Piotto 2008). Montagnini et al. (2004) and Petit and Montagnini (2006) further argued that certain species could act as “nurses” to other tree species and that a combination of fast-growing and slower-growing tree species can produce timber and more valuable wood products while simultaneously reducing the risks of soil erosion and providing shelter and protection against frost or pests.

The findings of the present study are consistent with those of previous studies conducted in Bangladesh, which have shown that mixed plantations of timber tree species exhibit better survivability and initial growth performance compared to mono plantations. For instance, Hossain et al. (1997) observed that mixed plantations of *Eucalyptus camaldulensis* and *Acacia auriculiformis* had higher tree height, stem diameter, and biomass accumulation than mono plantations of either species alone. Similarly, Dutta and Hossain (2017) found that the initial growth performance of *A. auriculiformis* and *Gmelina arborea* performed better in mixed plantations than in mono plantations. Another study by Dutta and Hossain (2018) recorded that mixed plantations of *A. auriculiformis* and *Swietenia mac-*

rophylla had higher tree height, diameter at breast height, and volume growth compared to mono plantations. Therefore, based on these previous findings, it can be inferred that planting Sal trees in mixed plantations could be a beneficial silvicultural practice for restoring degraded Sal forest land in Bangladesh.

Conclusion

This study is designed as a preliminary investigation to assess the impact of mono and mixed plantations of Sal in conjunction with four associated and two naturally grown tropical timber tree species on the survival and initial growth performance under field experiment plots in degraded Sal forest areas of Bangladesh. The results of the experimental plots in 2019 and 2020 demonstrate that Sal trees have high survivability rates and exhibit impressive initial growth performance when planted in mixed plots with compatible associate and naturally grown tree species. These findings suggest that planting Sal trees in combination with compatible associated and naturally grown tree species would be more effective than mono plantations for restoring degraded Sal forest areas in Bangladesh. However, it is recommended that further research be conducted with the associated and naturally grown tree species at the field level prior to implementing large-scale afforestation, reforestation and restoration programs in the Sal forest ecosystem of Bangladesh.

Certain challenges emerged during the execution of the present studied experiments and methodology. Specifically, identifying the optimal tree species for Sal was constrained by scale limitations, resulting in data collection being limited to a preliminary stage. Limitations in resources may restrict the number of species studied. Preliminary data collection might not provide comprehensive insights into the long-term viability and ecological impact of the plantation. To gain a deeper understanding and determine the precise significance and interrelationship between Sal and its compatible, naturally grown tree species, further replication and the establishment of mature plantations are imperative. Finally, limited replication due to resource constraints can affect the generalizability and robustness of the findings.

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