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Restoration of forests: Examining tree species diversity and growth for successful ecosystem restoration in Pakistan

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Abstract

Restoration of degraded ecosystems is crucial for the conservation of biodiversity and the provision of ecosystem services. In this study, we evaluated the success of forest restoration efforts in Buner District, Pakistan, by assessing tree species diversity and forest structure. The study area was divided into assisted natural regeneration sites and plantations. Altogether thirty sites (by fifteen for assisted natural regeneration and for plantations) were randomly selected, covering the entire area. The result revealed that the assisted natural regeneration sites comprised thirteen diverse species dominated by *Pinus roxburghii* (54.78%), followed by *Dodonaea viscosa* (12.14%). In comparison, the plantation sites consisted of sixteen various species dominated by *Eucalyptus camaldulensis* (77.45%), followed by *Robinia pseudoacacia* (8.77%). The results further indicated that the average survival rate of the study area was 58.49% with the highest survival rate of 82.45% at the Ambela site and the lowest survival rate of 37.04% at the Budal site. Moreover, the number of exotic species used in plantations was limited; however, their proportion in the study area was much higher (91.15%) than that of the indigenous species (8.85%). A correlation matrix was developed to understand the relationship between seedling density (as a dependent variable) in naturally regenerating sites and influencing factors (as explanatory variables). Results showed that grazing, grass cutting, mean temperature and disturbance negatively correlated with seedling density, whereas elevation and annual precipitation positively correlated. Also, a stepwise linear regression model between seedling density and influencing factors was developed.

Keywords: species composition; *Pinus roxburghii*; assisted natural regeneration; tree plantations; survival rate; forest disturbance

Introduction

The rapid deforestation rate worldwide has resulted in many negative environmental issues, such as air pollution, biodiversity loss, desertification, and climate change. The adverse impact of climate change is more evident today and has been reported around the world in the shape of wildfires (Williams et al. 2019), droughts and floods (Huang et al. 2015), sea-level rise (Nerem et al. 2018), and food security problems (Masipa 2017). As a result of climate change, wildfires are more frequent in many parts of the world. In 2019, a wildfire in South Wales had badly affected forests and other natural vegetation over about 2.7 million hectares (Yu et al. 2020). Less rainfall and increasing temperature are significant factors of bushfires. Recently, an area of 906,000 hectares was affected by wildfires in Amazon (Yu et al. 2020). The rising global mean temperature will harm different ecosystem services. Climate change effects are likely to be earliest in tropical regions. Forests which are considered to be natural tools to mitigate climate change are themselves at risk (Albrich et al. 2020). The Intergovernmental Panel on Climate Change (IPCC) reports also warn the world of the detrimental effects of climate change if not addressed sooner (Molina and Abadal 2021).

Forest ecosystems provide various services to humankind; they are the following: timber, fuelwood, fodder, medicinal plants, water purification, regulating surface temperature, clean air, aesthetic value, erosion and flood control. Besides, forests are home to millions of wildlife species. Forests store carbon dioxide, a greenhouse gas, and give oxygen to all living creatures. Millions of people worldwide depend on forest resources, especially in developing countries. The reduction in ecosystem services has been reported due to the decline of forest cover (Tolessa et al. 2017). “Less than half of the world’s tropical forests remain standing” (Lewis et al. 2015), and existing forests are insufficient to maintain biodiversity and deliver the multiple ecosystem services essential for rapidly rising human populations (Houghton et al. 2015, Martínez-Ramos et al. 2016). Therefore, restoration of degraded forests and their functionality is crucial at a large scale. In the tropics, more than a billion hectares of degraded land (forest and woodlots) can be restored in several ways (Chazdon and Uriarte 2016).

In the view of ecosystem restoration, the selection of monoculture and mixed-species plantations is controversial and still under debate, but researchers recommend mixed-species plantations due to the growing climate crisis and biodiversity loss (Brockerhoff et al. 2017, Liu et al. 2018). Furthermore, the diversified forests are more resistant, durable, and adaptable to global change (Pretzsch et al. 2017). Wang et al. (2019) also reported from their study that mixed-species plantations are more beneficial for biodiversity than monoculture plantations. Further the study suggested that the priority should be given to the conservation and restoration of native forests, but mixed-species plantations should be used in afforestation. Liu et al. (2018) also recommended mixed-species plantations with up to four species, emphasizing that they are more productive and have more significant advantages in biodiversity, economy, and forest health than monocultures with careful planning and management. According to Gong et al. (2021), mixed-species plantations enhance soil carbon stock and improve soil health. Similarly, Gong et al. (2020) concluded through meta-analysis that mixed-species plantations are beneficial to increasing drought resilience in arid and semi-arid areas. Problems like displacement of native biodiversity, mainly due to the destruction of non-forest ecosystems (Seddon et al. 2019), an increase in invasive species (Kull et al. 2018), a decrease in aboveground carbon stock (Heilmayr et al. 2020) and a reduction in soil organic carbon (Hong et al. 2020) are primarily associated with the extensive use of exotic monoculture plantations rather than restoration approaches that encourage a diverse, carbon-rich mix of native tree species (Brancalion et al. 2018, Heilmayr et al. 2020, Lewis et al. 2019).

Assisted natural regeneration and plantations are the two methods mostly used for forest ecosystem restoration worldwide. Forest plantations offer a number of benefits, playing an important role in ecosystem functionality (Hector and Bagchi 2007), mitigating climate change through carbon sequestration (Kongsager et al. 2012) and carbon storage (Chen et al. 2015), supporting effective nutrient cycling (Ma et al. 2007), improving tree diversity and forest structure (Eycott et al. 2006), control soil erosion (Lawson and Michler 2014) and enhancing other ecosystem services. Trees help to control stream flow and dampen the amplitude of peak flows (Buendia et al. 2015) and retain more water in the soil (Bonnesoeur et al. 2019). The advantage of afforestation is that on one hand, it reduces deforestation by timber production (Pirard et al. 2016), and strengthens local ecosystem functions on the other hand (Sukhbaatar et al. 2020). Yet, it can be hard to establish forest plantations as different factors affect the survival and growth of seedlings. Various studies have reported that variation in the survival rate and growth performance of seedlings could be due to limited light availability (Collin et al. 2017, Jin et al. 2018, Kardiman et al. 2019), nutrient deficiencies (Löf et al. 2007), interspecific competition (Marron et al. 2018), and changing environmental factors (Hattori et al. 2013). Most of the time, plantations are established on open sites to accelerate forest recovery mechanisms. However, Löf et al. (2007) reported that the survival rate of plantations on open sites is lower than those established under indigenous tree canopies.

Plantation success is detemined by environmental conditions, which influence the capacity of seedlings to survive local stressors in their early stages. Since plants range in their capacity to fix carbon, it is necessary to identify criteria so that appropriate species may be selected for carbon offset and restoration projects (Kaul et al. 2010). A database of native plant performance under various environmental circumstances can improve the effectiveness of restoration efforts by allowing for the selection of more suitable species (Rodrigues et al. 2009, Breugel et al. 2011, Meli et al. 2014). Moreover, the evaluation of plantations at an early stage is important to provide a baseline for future studies. For instance, according to Paudel and Acharya (2016), millions of hectares of land have been planted with trees in Nepal in the past but planting project managers do not have accurate data on the established plantations due to the lack of in-time assessment. Therefore, assessment of plantation sites is necessary to measure the project achievement as well as to determine potential failure sites for further improvement.

The main objectives of this study were: (i) to evaluate the species composition of natural regeneration and plantations; (ii) to assess the survival rate of plantations as well as to evaluate the growth performance of species growing in natural forest and plantations; and (iii) to examine the effects of different influential factor on seedling density and survival rate of plantations.

Materials and methods

Study area

This study was conducted in Buner District, the Malakand division of the Khyber Pakhtunkhwa province, located between latitude 34°10' 10'' N 34°43' 05" N and longitude 72° 11' 30'' E and 72° 49' 10" E (WGS84) (Figure 1). The district is surrounded by Swat District on the north, Malakand District on the west, Mardan District on the south, and the Indus river and Hazara division on the east (Sulaiman et al. 2020). The elevation of the area ranges from 366 m in Totalai in the south to 2,911 m of Dosara peak in the north. Buner District is surrounded by chains of hills on all sides and is separated from Swat by a range of mountains.

The climate of the study area varies from dry subtropical to sub-humid temperate since the territory stretches forth from around 366 m to roughly 3,046 m in height. During the monsoon (July–September), the entire area receives rain. In winter, snow begins to fall in December

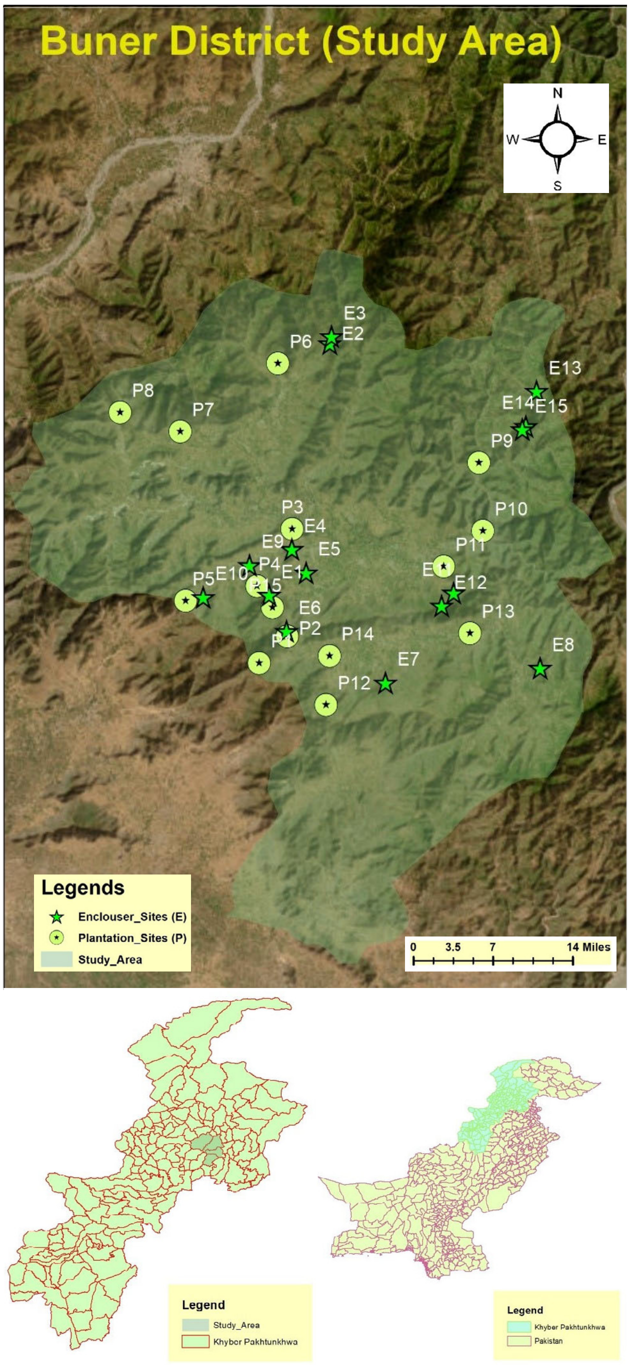

Figure 1. The map of study area

and continues until March. Snow falls above 1500 m a.s.l., but it melts quickly up to 2,000 m elevation, except on cool northern slopes and in sheltered places. By the end of March or at the start of April, hilltop snow melts completely. During May and June, the weather is dry and hot. The arrival of monsoon rains in July brings an end to the sweltering weather. October and November always remain dry. Frost is observed from December to March. During the winter season the weather always remains foggy. The average weather data of Buner District (1980–2016) is presented in Table 1.

Table 1. Average weather data of District Buner

Month	Avg low temp (°C)	Avg high temp (°C)	Rainfall (mm)	Days of rain
January	2.78	15.56	30.48	3.9
February	5	17.22	66.04	6.2
March	9.4	22.22	73.66	8.4
April	15	27.78	55.88	6.8
May	18.89	32.78	25.4	4.6
June	22.22	35.56	27.94	5.1
July	24.44	35	76.2	10.3
August	23.89	34.44	73.66	9.7
September	20.56	33.33	33.02	5.4
October	14.44	28.33	22.86	3.4
November	7.78	22.78	15.24	1.9
December	3.89	17.22	20.32	2.5

Source: Daggar Climate, Weather By Month, Average Temperature (Pakistan) – Weather Spark, n.d.

Methods

According to the office record of Divisional Forest Officer, a total of 372 sites have been established in Buner District under the Billion Tree Afforestation Project (BTAP). Out of these, 30 sites were randomly selected covering the entire study area. The study area was divided into assisted natural regeneration sites (enclosures) and man-made regeneration (plantations). From each type, 15 sites were randomly selected, covering the whole area. The description of each site is presented in Table 2.

Table 2. Details of site location along with the number of plots in each site

Location	No of plots	X	Y	Elevation
		Plantations		
Ambela	7	3151114	1131979	853
Spalam	8	3153376	1134444	799
Karapa	9	3153164	1143742	836
Mula Yousaf	5	3150462	1138622	811
Sarmalang	8	3144390	1136939	877
Pirbaba	5	3150972	1157901	863
Katkala	4	3142955	1151495	801
Leganai	5	3137665	1152771	924
Batara	7	3168850	1150537	901
Budal	7	3169579	1144681	762
Kulyari	5	3166437	1141380	729
Durmai	7	3157085	1128777	970
Makhranai	8	3169062	1135782	706
Koga	4	3157108	1132989	683
Barkalay	12	3151925	1136877	880
		Enclosure		
Barkalay	6	3151556	1137947	927
Kalil	6	3155293	1159969	1,379
Kalil	9	3155426	1160604	1,494
Rega	9	3153243	1142030	790
Cheena	6	3154607	1140089	789
Ambela	5	3153250	1134937	957
Sura	7	3162080	1131080	741
Charorai	5	3175289	1133222	1,018
Mula Yousaf	7	3149681	1140423	808
Nawakalay	5	3145868	1137394	836
Kulyari	6	3167408	1139205	1,039
Kulyari	8	3166461	1138014	1,012
Bartiraj	7	3173379	1157053	1,731
Chalandrai	5	3172668	1153978	1,488
Chalandrai	6	3172388	1153685	1,460

Plot selection

At each site, at least 5 circular sample plots of 250 m^2 area were laid out to collect data in the field. A total of 97 sample plots were laid out in the enclosure sites, while 98 sample plots were laid out in the plantation sites. *Pinus roxburghii* (chir pine) occurred in 56 sample plots in natural forests, while in the plantation sites it only occurred in 18 sample plots. The distance between plots was kept at 100 m to cover any variation due to local factors. A simple random sampling technique was used for data collection. GPS was used to record the coordinates of the sample plots. The data was collected from October 2020 to December 2020.

Species composition

Each sample plot species with a name was recorded in a Proforma on the spot and later was recorded into MS Excel spreadsheet for further analysis. The species proportion was determined through species density. Each species was counted in a site at the plot level divided by the total number of species calculated and multiplied by 100 (Formula 1). Species proportion was calculated for each site as well as for the entire study area.

$$\text{Species proportion (\%)} = \frac{\text{Number of individual species in a site}}{\text{Total number of species}} \cdot 100 \quad (1)$$

Survival rate of plantations

To assess the survival rate of plantations, a Proforma was developed. The Proforma contains the information of site, plot number along with coordinates, and species details. Information from the site was recorded in this Proforma for further analysis. The survival rate of planted seedlings on each plot was evaluated through counting both live and dead individuals (Ullah et al. 2020). Through the assessment of survival rate, the success or failure of plantations was determined. The survival rate of plantation was determined through the pit density and empty pits data. The survival rate depends on how much out of the total planted individuals survived and could probably become healthy plants in future (Formula 2; WWF-Pakistan 2016). The greater the number of empty pits the lesser the survival percentage of the site and *vice versa*. Plotwise survival rates were converted to sitewise survival rates by using pit density data and plantation area.

$$S_p = \frac{N_e}{N_t} \cdot 100 \ , \quad (2)$$

where:
S_p – the survival percentage,
N_e – the number of empty pits per hectare,
N_t – the number of total pits per hectare.

In addition, information on forest wildfire occurrences was obtained from forest officials, field observations of burned areas, and insights provided by local residents (Kumar et al. 2022). Livestock grazing activities were assessed by observing grazing animals, identifying grazing patterns, and noting the presence of dung and indirect signs such as animal footprints (Shekhar Silori 2004). Moreover, information on grass cutting was gathered through field observations and informal interview-based discussion with local people (Ogra and Badola 2008). The disturbances were categorized as no disturbance, low, moderate, or recurrent, based on the information provided by the local people and field observations. This classification was adapted from the disturbance classification method proposed by Kumar and Saikia (2021), which originally categorized disturbances as occasional and recurrent, with modifications made to align with the objectives of our study. The weather data were acquired from WorldClim Global climate data (WorldClim 2024). Bioclimatic variables (of 30 arc seconds resolution) consisting of Annual Mean Temperature and Annual Rainfall values were retrieved from Fick and Hijmans (2017).

Growth performance of species

The developed Proforma was used also to assess the growth performance of *Pinus roxburghii* in the plantations and enclosures. Information from the site was recorded in this Proforma for further analysis. To assess the growth performance of species, measurement of both the diameter at base and tree height was required. Due to the limited resources and uncertain situation of COVID-19, it was difficult to measure the height of each tree for fast growing species. Therefore, this study has focused to comparatively assess the growth performance of naturally regenerated and artificially planted *Pinus roxburghii* species. The diameter and height of the trees were measured to calculate growth performance of *Pinus roxburghii*. On the other hand, only the diameter at base of broadleaved species growing in natural forest and plantations were measured. The mean diameters of broadleaved species occurred in enclosures and plantations were compared.

Statistical analysis

Descriptive statistics such as percentage and mean as well as graphs were developed using MS Excel spreadsheet. Correlation matrixes of seedling density of enclosure and survival rate of plantation were developed in R-statistical software (R Core Team 2024). Stepwise linear regression (SLR) model was developed for seedling density (of enclosure) and survival rate (of plantation) against various influencing factors (such as grazing, grass cutting, fire disturbance, elevation, and temperature) using a SPSS 16.0 software package (IBM 2007). Stepwise linear regression is a statistical method used to determine the most significant set of independent variables to predict a dependent variable. It involves adding and removing variables from a model in a stepwise manner, based on their statistical significance, until the most significant model is achieved.

Results

Species composition

Enclosure (assisted natural regeneration)

In all fifteen (15) enclosure sites, thirteen different types of tree species were present. Among them, two species belong to conifers: *Pinus roxburghii* and *Pinus wallichiana*, while the rest of the eleven (11) species belong to broadleaved plants: *Eucalyptus camaldulensis*, *Mallotus philippensis*, *Dodonaea viscosa*, *Ficus religiosa*, *Robinia pseudoacacia*, *Ailanthus altissima*, *Melia azedarach*, *Dalbergia sissoo*, *Quercus incana*, *Olea ferruginea*, and *Celtis australis*.

Pinus roxburghii was the most dominant species with about 54.78% of the study area, followed by *Dodonea viscosa*, approximately 12.14%. The least occurring species was *Celtis australis*, about 0.10%, followed by *Ficus religiosa* with 0.16%. The species composition of the whole study area is presented in Figure 2, while each site species' composition is presented in Table 3. Moreover, the highest mean density was calculated at site 3, counting for 3,817 plants per hectare (ha), while the lowest mean density was estimated at site 10 with 616 individuals per ha. The overall average density was 1,384 trees per ha (Table 3). The elevation of the enclosure plots ranged from 700 m to 1,741 m a.s.l., with a mean height of 1,165.63 m a.s.l.

Plantations

The highest pit density was found to be 1,550 pits ha^{-1} at Katkala, while the lowest pit density was 640 pits ha^{-1} at Koga. The average pit density of all sites was 970 pits ha^{-1}. In all 15 sites of plantations, sixteen (16) different types of species were found. Among them, one species was a conifer, *Pinus roxburghii*, while the rest of the fifteen (15) species were broadleaved trees. *Eucalyptus camaldulensis* was the single dominant tree species with about 77.45%, followed by *Robinia pseudoacacia* and *Ailanthus altissima* with 8.77% and 4.35%, respectively. *Pinus roxburghii* proportion of the study sites was about 3.19% (Figure 2). All other broadleaved species, namely *Melia azedarach*,

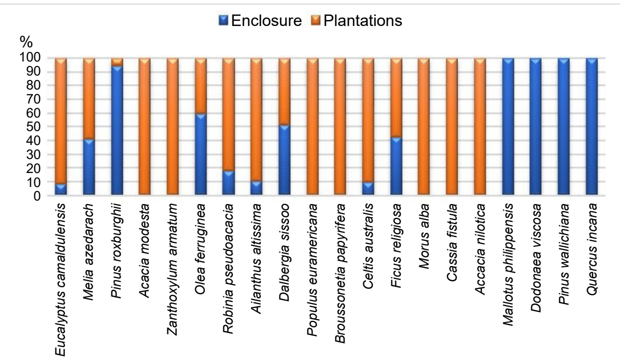

Figure 2. The species' composition of the natural regeneration and plantation sites

Table 3. Species names, percentage, and mean density in each enclosure and plantation site

Site location	Species name	Species percentage (%)	Mean density (ha^{-1})
	Species proportion (Enclosure)		
Barkalay	*Eucalyptus camaldulensis*	6.12	1,526.8
	Mallotus philippensis	51.02	
	Dodonaea viscosa	42.86	
Kalil (C23)	Pinus roxburghii	97.47	1,320
	Ficus religiosa	1.01	
	Robinia pseudoacacia	1.52	
Kalil (C22)	*Pinus roxburghii*	96.40	3,817.6
	Robinia pseudoacacia	3.60	
Rega	*Pinus roxburghii*	28.40	1,060
	Eucalyptus camaldulensis	22.22	
	Olea ferruginea	11.11	
	Mallotus philippensis	1.23	
	Robinia pseudoacacia	1.85	
	Dodonaea viscosa	31.48	
	Robinia pseudoacacia	3.70	
Cheena	*Eucalyptus camaldulensis*	91.45	780
	Pinus roxburghii	8.55	
Ambela	*Ailanthus altissima*	8.42	680
	Mallotus philippensis	42.11	
	Dodonaea viscosa	48.42	
	Eucalyptus camaldulensis	1.05	
Sura	*Eucalyptus camaldulensis*	4.76	594.4
	Melia azedarach	16.19	
	Pinus roxburghii	23.80	
	Robinia pseudoacacia	19.05	
	Ailanthus altissima	7.62	
	Olea ferruginea	6.67	
	Dalbergia sissoo	6.67	
	Ficus religiosa	2.86	
	Mallotus philippensis	12.38	
Charorai	*Pinus roxburghii*	100	1600
Mula Yousaf	*Eucalyptus camaldulensis*	11.26	862.8
	Dodonaea viscosa	74.83	
	Olea ferruginea	5.30	
	Mallotus philippensis	8.61	
Nawakaly	*Pinus roxburghii*	87.01	616
	Mallotus philippensis	12.99	
Kulyari (C10)	*Pinus roxburghii*	16.31	1,553.2
	Dodonaea viscosa	18.45	
	Mallotus philippensis	65.24	
Kulyari (C8)	*Pinus roxburghii*	11.11	1,305.2
	Dodonaea viscosa	39.08	
	Mallotus philippensis	27.59	
	Eucalyptus camaldulensis	22.22	
Bartiraj	*Pinus wallichiana*	47.11	1,925.6
	Quercus incana	52.89	
Chalandrai (C14)	*Pinus roxburghii*	100	688
Chalangrai (C15)	*Pinus roxburghii*	100	1,153.2
			1,384.17
	Species proportion (Plantation)		
Ambela	*Eucalyptus camaldulensis*	87.40	1,760
	Pinus roxburghii	10.24	
	Cassia fistula	2.36	
Spalam	*Eucalyptus camaldulensis*	92.16	870
	Acacia modesta	4.58	
	Acacia nilotica	2.61	
	Dalbergia sissoo	0.65	

Table 3. (continued)

Site location	Species name	Species percentage (%)	Mean density (ha⁻¹)
Krapa	*Eucalyptus camaldulensis*	85.32	1,275.6
	Acacia modesta	7.34	
	Melia azedarach	5.50	
	Pinus roxburghii	1.83	
Mula Yousaf	*Eucalyptus camaldulensis*	100	2,336
Sarmalang	*Eucalyptus camaldulensis*	93.80	1,865.2
	Zanthoxylum armatum	3.10	
	Pinus roxburghii	3.10	
Pirbaba	*Eucalyptus camaldulensis*	96.23	1,120
	Acacia modesta	1.89	
	Olea ferruginea	1.89	
Katkala	*Eucalyptus camaldulensis*	26.4	2,370
	Robinia pseudoacacia	4	
	Ailanthus altissima	44	
	Pinus roxburghii	9.6	
	Ficus religiose	2.4	
	Morus alba	0.8	
	Celtis australis	9.6	
	Melia azedarach	3.2	
Leganai	*Eucalyptus camaldulensis*	90	840
	Pinus roxburghii	10	
Batara	*Robinia pseudoacacia*	86.57	1,253.2
	Ailanthus altissima	1.49	
	Eucalyptus camaldulensis	10.45	
	Acacia modesta	1.49	
Budal	*Eucalyptus camaldulensis*	66.67	388.4
	Olea ferruginea	15	
	Acacia modesta	15	
	Dalbergia sissoo	3.33	
Kulyari	*Eucalyptus camaldulensis*	100	720
Durmai	*Eucalyptus camaldulensis*	100	868.4
Makhranai	*Eucalyptus camaldulensis*	95.35	1,070
	Pinus roxburghii	4.65	
Koga	*Eucalyptus camaldulensis*	55.17	420
	Populus euramericana	10.34	
	Broussonetia papyrifera	17.24	
	Melia azedarach	3.45	
	Celtis australis	3.45	
	Ailanthus altissima	10.35	
Barkalay	*Eucalyptus camaldulensis*	94.85	530
	Pinus roxburghii	5.15	
			1,131.6

Note: C – compartment.

Acacia modesta, *Zanthoxylum armatum*, *Olea ferruginea*, *Dalbergia sissoo*, *Populus euramericana*, *Broussonetia papyrifera*, *Celtis australis*, *Ficus religiosa*, *Morus alba*, *Cassia fistula*, *Acacia nilotica*, were about 6.24%. The data on species composition in each site is presented in Table 3.

The highest average density was estimated at site 7 with 2,370 individuals per hectare, while the lowest density was found at site 10 with 388.4 individuals per ha. The highest density recorded at some sites was due to the strong coppice system of *Eucalyptus camaldulensis*. Overall, the mean density for the plantation was estimated as 1,131.6 individuals per ha (Table 3). The elevation of the plantation sites ranged from 669 m to 1,026 m, with a mean elevation of 832.94 m a.s.l. The proportions of native and non-native species at the plantation sites were also calculated. Among the mentioned sixteen tree species, six were exotic while other ten species were indigenous at the plantations of the study area (Table 4). The proportion of non-native species was 91.15%, whereas the proportion of indigenous species was 8.85%.

Table 4. Native and exotic species found in the plantations

S. No.	Species name: Scientific name	Species name: Common name	Species status (affiliation with Pakistani flora)
1	*Acacia modesta*	Phulai, Palosa	Native
2	*Acacia nilotica*	Kikar	Native
3	*Ailanthus altissima*	Asmani, Tree of Heaven	Exotic
4	*Broussonetia papyrifera*	Paper Mulberry	Exotic
5	*Cassia fistula*	Amaltas	Native
6	*Celtis australis*	European hackberry	Native [a]
7	*Dalbergia sissoo*	Shisham	Native
8	*Eucalyptus camaldulensis*	Sufeda, Lachi	Exotic
9	*Ficus religiosa*	Pipal	Exotic
10	*Melia azedarach*	Bakain	Native
11	*Morus alba*	Mulberry	Native
12	*Olea ferruginea*	Kahu	Native
13	*Pinus roxburghii*	Chir pine	Native
14	*Populus euramericana*	Hybrid poplar	Exotic
15	*Robinia pseudoacacia*	Black Locust, Robinia	Exotic
16	*Zanthoxylum armatum*	Prickly ash	Native [b]

Source: Sheikh 1993, Hatamian et al. 2020 [a], Phuyal et al. 2018 [b].

Survival rate

The average survival rate of trees at all sites in the plantation was 58.49%, where the highest average survival rate was found to be at Ambela with 82.45%, while the lowest survival rate was recorded at the Budal site, 37.04% (Table 5). Similarly, the highest survival rate at a plot level was 100% at the Ambela and Katkala sites, while

Table 5. Sitewise detail of pit density and survival rate of plantations

Location name	Avg pits per plot	Pits / ha	Total Pits in site	Fail pits / plot	Fail pits / ha	Total fail pits	Survival %
Ambela	22	880	37,840	3.86	154.4	6,639.2	82.45
Spalam	29	1,160	98,600	9.88	395.2	33,592	65.93
Krapa	25.33	1,013.2	87,135.2	13.22	528.8	45,476.8	47.81
Mula Yousaf	24	960	35,520	7	280	10,360	70.83
Sarmalang	20.63	825.2	123,780	8.5	340	51,000	58.80
Pirbaba	21	840	50,400	10.4	416	24,960	50.48
Katkala	38.75	1,550	62,000	7.5	300	12,000	80.65
Leganai	24.6	984	44,280	14.6	584	26,280	40.65
Batara	31.5	1,260	50,400	9.17	366.8	14,672	70.89
Budal	23.14	925.6	37,024	14.57	582.8	23,312	37.04
Kulyari	22.8	912	41,952	13.8	552	25,392	39.47
Durmai	24.29	971.6	82,586	5.86	234.4	19,924	75.87
Makhranai	22.25	890	53,400	11.5	460	27,600	48.31
Koga	16	640	25,600	6.33	253.2	10,128	60.44
Barkalay	18.45	738	123,984	9.64	385.6	64,780.8	47.75
Average		970					58.49

the lowest survival rate at a plot was 10% at the Budal site. Moreover, we observed that, at 60% of the sites (i.e. nine out of fifteen sites), the survival rate was above 50%, where 33% of sites show a high survival percentage; above 70%, and 27% of the sites shows average survival percentage; 50–70%, while the rest of the 40% sites, i.e. six sites, shows low survival percentage; below 50%.

Growth performance

The mean diameter at the base and mean height of *Pinus roxburghii* growing in the enclosure was 1.2 cm and 1.15 m, respectively. In comparison, the mean diameter at the base and mean height of the *Pinus roxburghii* growing in plantations were 5.86 cm and 3.55 m, respectively. The difference in mean diameter and mean height between the two forest regeneration types was due to age differences. Mean heights (m) against each diameter class of the enclosure and plantation sites are presented in Table 6. Most plants are recently regenerated in the enclosures as most of the species' regeneration density was less than 1 cm (see Table 6 and Figure 3); at the plantation sites the age of trees were 3–5 years.

As mentioned earlier, due to the limited time and resources, only the diameter at the base of other species

Table 6. Mean height and density of enclosure and plantation for each diameter (at base) class

S. No.	Diameter (cm)	Mean density (plants/ha)	Mean height (m)
		Enclosure	
1	< 1	1145	0.52
2	1	393.1	1.2
3	2	183.53	1.85
4	3	179.05	2.32
5	4	156.36	3.3
6	5	90.91	4.98
7	6	62.86	5.37
8	7	120	5.73
9	8	66.67	6.58
10	9	80	7.15
11	10	96	7.93
12	11	120	8.72
13	12	130	9.07
		Plantation	
1	< 1	-	-
2	1	64	1.04
3	2	80	1.42
4	3	120	1.9
5	4	88	2.39
6	5	53.3	2.7
7	6	40	3.55
8	7	-	-
9	8	40	4.5
10	9	-	-
11	10	-	-
12	11	40	8
13	≥ 12	53.33	9.88

Note: The basal diameter, mean height, and mean density are related to *Pinus roxburghii* only.

Figure 3. Chir pine older regeneration (on the left) and younger regeneration (on the right)

Table 7. Basal diameter of species grown in the enclosures and plantations

S. No.	Species	Diameter at base (cm)	
		Plantations	Enclosures
1	*Eucalyptus camaldulensis*	1.65	2.39
2	*Robinia pseudoacacia*	1.17	1.51
3	*Ailanthus altissima*	0.98	0.91
4	*Melia azedarach*	1.78	1.06
5	*Acacia modesta*	1.59	-
6	*Zanthoxylum armatum*	1.93	-
7	*Olea ferruginea*	2.95	0.58
8	*Dalbergia sissoo*	6.27	1.5
9	*Populus euramericana*	2.33	-
10	*Broussonetia papyrifera*	2.25	-
11	*Celtis australis*	0.77	0.97
12	*Ficus religiosa*	5.5	1.24
13	*Morus alba*	6.4	-
14	*Cassia fistula*	3.73	-
15	*Acacia nilotica*	1.05	-
16	*Mallotus philippensis*	-	0.78
17	*Dodonea viscosa*	-	0.42
18	*Pinus wallichiana*	-	0.84
19	*Quercus incana*	-	0.18

that occurred in the enclosures and plantations was measured. The basal diameter of each species is presented in Table 7. *Eucalyptus camaldulensis*, *Robinia pseudoacacia*, and *Celtis australis* recorded in the enclosure sites (natural forests) showed greater basal diameter compared to that in the plantations, while *Ailanthus altissima*, *Melia azedarach*, *Olea ferruginea*, *Dalbergia sissoo*, and *Ficus religiosa* grown in the plantation sites attained higher basal diameter compared to the natural regeneration sites. Other species were encountered either in the enclosures or in plantations (see Table 7).

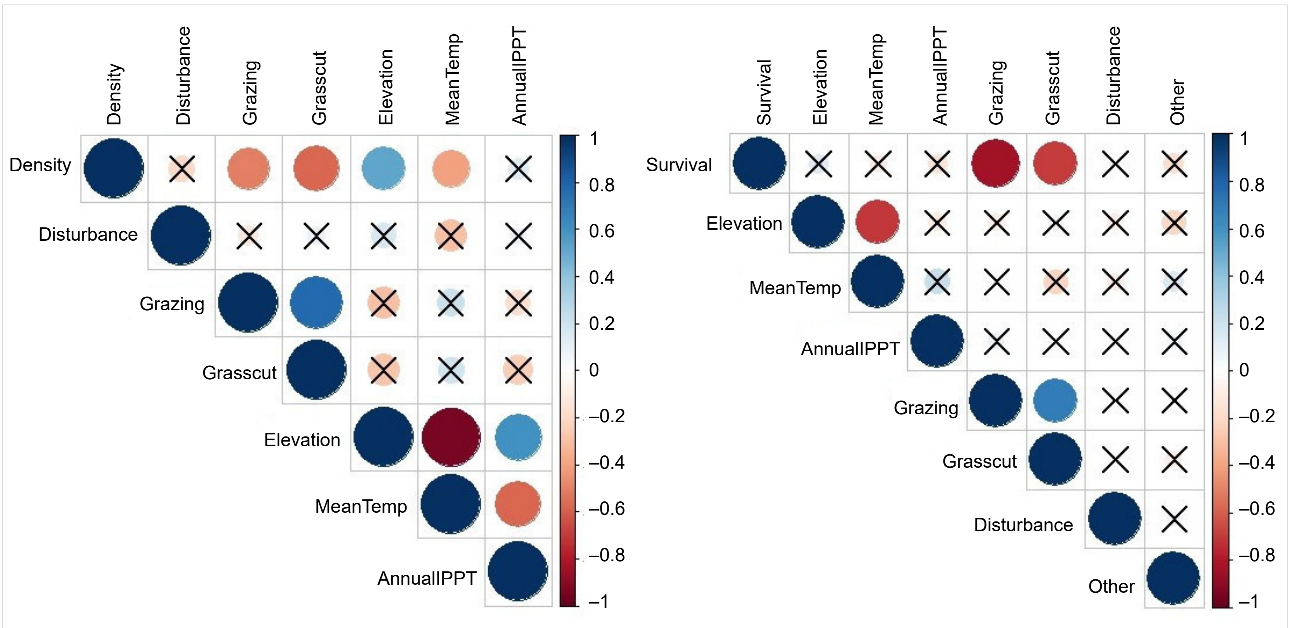

Figure 4. Correlation between seedling density in the natural regeneration sites and influencing factors (a) and the survival rate in the plantation sites and influencing factors (b)

Correlation between seedling density and survival against influencing factors

A correlation matrix was developed to understand the relationship between seedling density (as dependent variable) in the enclosures and influencing factors (as explanatory variables). Results showed that grazing, grass cutting, mean temperature and disturbance are negatively correlated with seedling density whereas elevation and annual precipitation positively correlated (Figure 4a). The highest correlation was shown between grass cutting and seedling density with *R*-value of –0.580 whereas the lowest correlation was observed between the mean temperature and seedling density with *R* of –0.408. Regarding other variables, correlation was –0.506 for grazing and 0.529 for elevation against seedling density, respectively. Moreover, the relationship of two variables, disturbance and annual precipitation, was insignificant (*P* is more than 0.05).

Similarly, a correlation matrix has been developed between the survival rate (as the dependent variable) in the plantation sites and various influencing factors (as explanatory variables). Results demonstrated that grazing and grass-cutting negatively correlated with a high level of significance, as presented in Figure 4b. The highest correlation was found between grazing and the survival rate, with a *R*-value of –0.834. Likewise, grass cutting also exhibited stronger negative correlation against the survival rate with *R*-value of –0.695. Furthermore, for the rest of the variables, the relationships between the disturbance, elevation, mean temperature, annual precipitation and other factors against the survival rate were statistically insignificant, with a *P*-value more than 0.05.

The size of the circles in the figures represents the magnitude of the coefficient correlation, with larger circles indicating stronger correlations and *vice versa*. The colour ramp, ranging from blue to red, signifies the direction of the correlation, where blue represents positive correlations and red indicates negative correlations. Symbol *X* represents no significant relationships.

A stepwise linear regression model for the seedling density and influencing factors

Factors that influence forest density (grass cutting, elevation, annual precipitation, disturbance (fire), grazing, mean temperature) were used as predictor variables in the stepwise regression model (Table 8). The final model selected explanatory variables based on significance level as the probability to be selected was ≤ .050 and the probability for exclusion was ≥ .100. As depicted in Table 8, the final model showed that grass cutting, elevation, annual precipitation and disturbance (fire) were selected as explanatory variables, while the rest of the influencing factors (grazing and mean temperature) were not excluded because their significance value is higher than the pre-defined threshold in the model. The overall coefficient of determination was 0.61 while the adjusted correlation was 0.58 with an error estimate of 893.68 (t/ha).

A stepwise linear regression model for survival rate and influencing factors

Outcomes of the stepwise linear regression (Table 9) showed that the model used all influencing factors that affect the survival rate as predictor variables,

Table 8. A stepwise regression model between seedling density and influencing factors

Variables entered/ removed [a]			Model summary				
Variables entered	Variables removed	Significance	*R*	*R* square	Adjusted *R* square	Std. error of the Estimate	
Grass cutting	-	0.000	0.783	0.613	0.583	893.68	
Elevation	-	0.000			ANOVA		
Annual PPT	-	0.002		Sum of squares	df	Mean square	F
Disturbance	-	0.013	Regression	6.457E7	4	1.614E7	20.211
	Grazing	0.38	Residual	4.073E7	51	798,673.9	
	Mean Temp	0.37	Total	1.053E8	55		
			Coefficients				
	Unstandardized coefficients		Standardized coefficients	t	Sig.	Model equation	
	B	S.E.				Density =	
(Constant)	5,861.275	1657.522	–.465	3.536	.001	5,861.27 – 601.62 ×	
Grass Cutting	–601.625	119.264	.654	–5.044	.000	Grass Cutting + 3.08 ×	
Elevation	3.082	.529	–.355	5.822	.000	Elevation – 5.53 ×	
Annual PPT	–5.531	1.708	–.231	–3.237	.002	Annual PPT – 384.5 ×	
Disturbance	–384.573	148.784	–.465	–2.585	.013	Disturbance	

Note: Dependent Variable : Density.
Predictors: (Constant), Grass cutting, Elevation, Annual PPT, Disturbance, Grazing, Mean Temp.
Stepwise (Criteria: Probability-of-F-to-enter ≤ .050, Probability-of-F-to-remove ≥ .100).

Table 9. A stepwise linear regression model between density and influencing factors

Variables entered/ removed [a]			Model summary				
Variables entered	Variables removed	Significance	*R*	*R* square	Adjusted *R* square	Std. error of the Estimate	
Grazing	-	.000	0.88	0.78	0.77	10.625	
Other	-	.000			ANOVA		
Grass Cutting	-	.000		Sum of squares	df	Mean square	F
Mean Temp	-	.009	Regression	37827.569	4	9456.89	83.76
	Disturbance	0.589	Residual	10499.625	93	112.89	
	Elevation	0.325	Total	48327.194	97		
	Annual PPT	0.459					
			Coefficients				
	Unstandardized coefficients		Standardized coefficients	t	Sig.	Model equation	
	B	S.E.				Survival =	
(Constant)	293.773	59.068	–.465	4.973	.000	293.77 – 16.80 ×	
Grazing	–16.804	1.836	.654	–9.153	.000	Grazing – 5.73 ×	
Other	–5.730	1.470	–.355	–3.897	.000	Others – 8.84 × Grass	
Grass Cutting	–8.846	2.015	–.231	–4.391	.000	Cutting – 8.31 ×	
Mean Temp	–8.311	3.097	–.465	–2.683	.009	Mean Temp	

Note: Dependent Variable : Density.
Predictors: (Constant), Grazing, Grass cutting, Others, Elevation, Annual PPT, Disturbance.
Stepwise (Criteria: Probability-of-F-to-enter ≤ .050, Probability-of-F-to-remove ≥ .100).

including grazing, grass cutting, others, elevation, annual precipitation and disturbance. The final model selected explanatory variables based on their significance level, where the probability of selection of ≤ .050 and the probability of exclusion of ≥ .100 were considered. Results in Table 8 demonstrated that the final model comprised grass cutting, grazing, others and mean temperature, whereas disturbance, the elevation and annual precipitation were not excluded due to their significance values exceeding the pre-defined threshold. The overall coefficient of determination was 0.78, while the adjusted correlation was 0.77, and the error estimate was 10.62.

Discussion

Species composition in the study area

Fortunately, the Billion Tree Afforestation Project has restored most of the area through assisted natural regeneration. To mitigate climate change consequences, to restore biodiversity, and to produce livelihood benefits, the protection of existing forests and the restoration of the native forests should be prioritised (Di Sacco et al. 2021). Yang et al (2018) also reported through their study that compared to other plantations, assisted natural regeneration enhanced ecosystem services like biodiversity protection, water and soil conservation, and carbon sequestration. Assisted natural regeneration is the cheapest and most cost-effective way to restore the degraded ecosystem and enhance ecosystem services (Chazdon and Uriarte 2016).

However, the mentioned researcher also suggests that native plantations should be established to restore the natural forests in those sites, where natural regeneration cannot work. For example, in our case, the result revealed that *Dodonaea viscosa*, a shrub, is the second dominant species in the enclosure sites, and it is necessary to plant native tree species in such sites. For the sites that are not fully restored in terms of density, plantations of mixed native species should be considered where it is possible. Overall, assisted natural regeneration is a good initiative to recover the natural forests; however, the weaknesses need to be addressed properly so that the objectives can be achieved in a better way.

In the presented study, the average pit density of 970 pits per ha is less than the required pit density of 1,075 ones per ha. Recently, in other studies, smaller pit densities at various locations were also reported (Alam et al. 2019, Ullah et al. 2020). The average pit density in the current study is more than 663 pits/ha (Alam et al. 2019), while it is less than the reported 1,065 pits/ha at the Dir lower plantation sites (Ullah et al. 2020) and 1,090 pits/ha at the Dera Ismail Khan forest division (Ali et al. 2023). The variation in pit density might be due to poor monitoring and inappropriate care. One another probable reason could be the accomplishment of a high target in a short duration. The plantations can be termed a monoculture when each site consists of one tree species with a proportion of above 80%.

Furthermore, plantations with diverse species composition are more robust and resilient to climate extremes compared to single-species (monoculture) plantations (Hutchison et al. 2018) and more resilient to pests and disease (Jactel et al. 2017). WWF-Pakistan (2016) stated in its report that *Pinus roxburghii* is the most planted species in the province with about 21% of the total species, whereas, in our study area, the species proportion is only 3%. The report also stated that few numbers exotic species are used in plantations, which is true (see Table 4); however, the proportion of non-native species is much higher in the present study area of the plantation, with only 9% of indigenous species proportion. It is recommended that further plantation of exotic species be avoided as much as possible and that the proportion of indigenous multiple tree species be increased to develop a resilient and diverse forest ecosystem. Moreover, species selection should be based on sound scientific restoration and biodiversity conservation principles. In addition, the preparation of a proper plan for reforestation activities and capacity building of the staff of the Forest Department to ensure landscape restoration may also be given attention.

The high proportion of exotic species, especially *Eucalyptus camaldulensis*, is of great concern. This eucalyptus species is controversial and has been listed as invasive in South Africa (Hirsch et al. 2019). Limited studies are available in Pakistan, mainly concerning groundwater tables (*see* Bilal et al. 2014, Nazli et al. 2020). No study on Eucalyptus impact on wildlife, understory vegetation, and soil has yet to be conducted in Pakistan.

WWF-Pakistan (2016) also reported that the number of *Eucalyptus camaldulensis* in the plantation is high. Other studies, such as Ali et al. (2023) also reported a high proportion of Eucalyptus species in plantations. The high proportion of *Eucalyptus camaldulensis* is being held responsible for the depletion of the groundwater table (Bilal et al. 2014).

One of the main reasons is that community lands have been used for plantations, and the species selection was purely based on their choices. Local people prefer the eucalyptus species because of its fast growth and high survival rate; also, it is considered a cash crop. However, mentioning one thing here is vital: the government is making all the investments, such as nursery establishment, labour cost on plantation, watering, and protection, and therefore the government should be equally involved in the decision of species selection.

Density

The overall average density of natural regeneration in the present study is higher than that of 670 individuals per ha found by Lodhiyal et al. (2015) and of 722.6 ± 151.0 per ha stated by Chauhan et al. (2008). The value of the present study is in the expected range of 925 ± 15 to 1,650 ± 22 per ha (Pokhriyal et al. 2012). The present study's value is comparatively higher than 1,000 trees per ha in the protected forest (Bargali et al. 2013). Studies show a higher regeneration density in less disturbed forests, while low regeneration density in the more disturbed forest (Sharma and Ahmend 2014, Baboo et al. 2017). The current study's value is lower than 1,830 trees per ha in the oak pine mixed forest (Manral et al. 2018). The density of the present study is in the expected range of 800 ± 12 to 1,850 ± 21 per ha (Pokhriyal et al. 2012). Our study value is relatively higher than 484.7 ± 35.1 per ha (Chauhan et al. 2008), and 321.5–398 trees per ha in mixed broadleaf forests (Arya and Ram 2019).

The study further revealed that the natural forest sites are recently regenerated as the density of small regeneration (i.e. diameter at the base less than 1 cm) was high compared to other diameter classes. Since most of the regeneration is newly grown and not established yet, our study suggests further protection of these natural sites for at least three more years to achieve the full establishment of this young regeneration.

Survival rate

Our result is comparable to the survival rate of seedlings on the plantations in Lower Kohistan, which is 63.99 (WWF-Pakistan 2016). Dajenea et al. (2018) also reported the lowest survival rate of 37%, the same as the current study's lowest survival rate. The third-party assessment report (WWF-Pakistan 2017) shows a high survival rate for the Phase-I and Phase-II plantations. They assessed the survival rate in the first year of the plantation; however, different anthropogenic and natural disturbances can affect the survival rate of the plantation in the subsequent years. Hence, continuous monitoring of the plantation sites is essential. Morais Jr. et al. (2019) reported the plantation's mean survival rate to be 47%, lower than the mean survival rate of 58.49% of the present study.

Another study on the seedling survival in different tree species in Brazil showed the survival rate to be 47.54% (Morais Jr. et al. 2020). The survival rate reported by Junaedi (2018), more than 60%, is within the expected range of the present study. One another study reported the average survival rate for all the plants to be 69% (Rawat et al. 2017). In this context, Madhu et al. (2017) also studied the survival rate of plantations and reported the survival rate as 77.43%. Similarly, Ullah et al. (2020) and Ali et al. (2023) studied the survival rate of plantation sites and reported that the survival rate of tree seedlings in the study area was above 80%. Sukhbaatar et al. (2020) reported that seedling survival of tree species is highly dependent on monthly rainfall and air temperature. The success of forest plantations is linked to environmental factors that influence the ability of seedlings to tolerate local stresses (Morais Jr. et al. 2019).

According to Khanal et al. (2018), low-quality seedlings and microsites (a site where the individual seedlings are planted) are the most significant factors in overall tree seedling survival. Moreover, the present study also showed a negative relationship of grazing with seedling survival in the plantations and regeneration density which is consistent with the findings of Fortuny et al. (2020), who reported the impact of overgrazing on seedling density in different species. This highlights the negative impact of grazing on young trees, especially in their vulnerable early stages. These external disturbances may be the main reasons for low survival and regeneration density in some sites.

The first year of any plantation is more critical concerning species survival (Khanal et al. 2018). However, monitoring of plantation sites is imperative until it is established. Different factors like rainfall, drought, humidity, and temperature affect the survival of seedlings (Sukhbaatar et al. 2020). The present study further revealed that a plantation could show a better survival rate of seedlings in the first year but it can face some natural and/or anthropogenic disturbances, ultimately reducing the survival rate of seedlings in the following year. Bertacchi et al. (2016) also stated that due to seasonal fluctuations in soil water supply, seedling survival rates may alter over time, thereby increasing seedling dieback.

The fast-growing species can establish early (i.e. 1–3 years, depending on the species and site), but the slow-growing species like *Pinus roxburghii* can take 5–8 years to be established. Therefore, continuous monitoring and conducting studies are necessary for plantation sites to know the species' performance condition. The different areas can face different natural and anthropogenic problems failing the plantations. Hence, monitoring as many plantation sites as possible is better to address any issue on time and make the plantations successful.

Growth performance

The mean height of *Pinus roxburghii* raised in the natural forest was comparatively higher than that of the plantation for each diameter class. This might be due to the most favourable conditions in the natural zones. The lower diameter recorded for some broadleaved plantations might be because they were recently regrown after harvesting. Natural regeneration was also observed at some of the plantation sites. It shows that natural regeneration can also occur at plantation sites if there are enough mother trees and they are protected from external disturbances such as grazing, fuel wood collection and grass cutting.

Furthermore, soil type differences may also account for variation in natural and artificial forest (Jõgiste et al. 2003). According to Sukhbaatar et al. (2020), variation in species height within a plantation could be more possibly due to the individual adaptation to the introduced environment. Another key component influencing tree growth is competition (Gradel et al. 2017). In natural stands, tree height is a major determinant of growth (Jõgiste et al. 2003). Growth rate and productivity are critical for managers to achieve economically viable outcomes (Niskanen 1999). Simultaneously, growth rate variables may be utilised to model changes in entire ecosystem processes (Jõgiste et al. 2003). To achieve satisfactory results in terms of species survival rate and growth performance, selecting the most favourable species according to their climatic zone is essential.

Ullah et al. (2020) studied the growth rate of a seventeen-month-old plantation and reported the mean girth and mean height for *Pinus roxburghii* as 4.15 cm and 0.59 m, respectively. The resource availability, the number of resources acquired, and the efficiency with which those resources are utilised all affect tree growth (Pretzsch et al. 2017). Sukhbaatar et al. (2020) studied the growth performance of Scots pine and reported that air humidity, temperature and precipitation are the contributing factors in species growth performance. Competition for resources is an essential factor affecting tree growth (Gradel et al. 2017). In another study, Poersch et al. (2017) reported that less rainfall and temperature negatively impact plant height.

Forest restoration success is critical not just for the sake of the region, but also for the sake of the world. The good survival rate and growth performance of tree species result in enhancement of ecosystem services including climate change mitigation. Most importantly trees are a renewable source of energy and are a great alternative to fossil fuel and could be an amazing eco-friendly fuel.

In short, the restoration campaign in the present study area can be considered successful concerning wood production, reducing pressure on natural forests, carbon sequestration, and other ecosystem services. However, it may not be effective in terms of biodiversity and resilience. Furthermore, the ecosystem services provided by these sites can be enhanced using mixed-species and native-species plantations. Actions are required to achieve various objectives such as restoring biodiversity, improving habitat for wildlife, protecting watersheds, and enhancing other ecosystem services. Therefore, these weaknesses require to be adequately addressed in the ongoing Ten Billion Tree Afforestation Project (TBTAP). To the best of our knowledge, this is the first attempt to assess critically the BTAP activities in the study area.

Conclusion

The study revealed that the assisted natural regeneration sites are comprised thirteen species, with *Pinus roxburghii* as the dominant species (54.78%), followed by *Dodonaea viscosa* (12.14%).

The plantation sites consisted of sixteen species, but were dominated by *Eucalyptus camaldulensis* (77.45%), with *Robinia pseudoacacia* as the second most common species (8.77%).

The proportion of exotic and native tree species in plantation sites was 91.15 and 8.85%, respectively, indicating a significant imbalance.

The high proportion of non-native species in the plantation sites is of great concern, and it should be reduced in the on-going restoration project.

The present study concluded that grazing, grass cutting, mean temperature, and fire disturbance negatively affected seedling density whereas elevation and annual precipitation had a positive influence.

In the plantation sites, the survival rate was significantly reduced by grazing and grass cutting, highlighting their strong negative impact on seedling establishment.

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