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Sustainable Harvesting and Regeneration Strategies for *Pinus wallichiana* in Pakistan's Himalayan Forests

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ABSTRACT

Blue pine (*Pinus wallichiana* A.B. Jacks.) carries much of the timber, fuelwood and watershed burden of the mountain belt between 2,200 and 3,400 m in northern Pakistan, yet the felling that supplies that demand is still being planned with yield tables and marking rules that predate most of what is now known about how the species actually regenerates. We combined stand inventory, regeneration sampling, tree-ring analysis and a household offtake survey across four valleys spanning a moisture gradient from the dry Karakoram (Naltar, Basho) through Astore to the moist temperate Western Himalaya (Kaghan). One hundred and twenty plots were distributed across four management regimes: legally protected stands, regulated single-tree selection, regulated group selection, and unregulated community harvesting. Group selection produced the highest seedling density (6,940 ± 703 ha^{-1}) and the strongest recruitment (505 ± 61 ha^{-1}), while unregulated stands failed the national stocking standard by a wide margin (1,510 ± 289 seedlings ha^{-1}; 44 ± 14 recruits ha^{-1}) and had lost the reverse-J diameter structure that indicates a self-replacing stand. Seedling establishment peaked under 50–70 % canopy cover but recruitment to breast height peaked under 30–45 %, so the two stages of regeneration have different and partly conflicting light requirements. Grazing pressure explained most of the variation in the seedling-to-sapling transition (R^2 = 0.92), which fell below 5 % once stocking exceeded roughly three livestock units per hectare per season. A 156-year ring-width chronology showed a 31 % rise in basal area increment since 1985 and a positive response to previous-November and summer maximum temperature, indicating that growth potential is currently rising while recruitment is falling. Measured offtake in unregulated stands (4.1 m^3 ha^{-1} yr^{-1}) exceeded mean annual increment (2.4–3.1 m^3 ha^{-1} yr^{-1}) by a factor of about 1.5, and a sixty-year projection under that regime halves the growing stock within 45 years. We propose an adaptive prescription built on group openings of 0.15–0.35 ha, an allowable cut capped at 60 % of measured increment, rotational grazing closure of five to seven

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years on regenerating gaps, and enrichment planting where stocking falls below 1,500 ha^{-1}. Under this combination the model returns a rising growing stock together with a cumulative sixty-year yield of about 111 m^3 ha^{-1}.

Keywords: Blue Pine; Uneven-Aged Silviculture; Group Selection; Natural Regeneration; Grazing Pressure; Karakoram; Allowable Cut; Adaptive Forest Management

Introduction

Pakistan is one of the least forested countries in South Asia. Depending on the definition used, forest covers somewhere between two and five per cent of the national territory, against roughly twenty-three per cent in India and twenty-five per cent in Nepal (FAO, 2020; Bukhari et al., 2012). Almost all of the high-value coniferous forest sits in a narrow altitudinal band along the Hindu Kush, Karakoram and Western Himalayan ranges, and almost all of it is under simultaneous pressure from timber extraction, fuelwood collection, livestock grazing and, increasingly, road access. Between 1990 and 2010 northern Pakistan lost around 1,707 km² of forest, about eight per cent of the standing area or 0.38 per cent per year, with Khyber Pakhtunkhwa and Gilgit-Baltistan absorbing most of that loss (Qamer et al., 2016; Ahmad et al., 2018).

Blue pine, *Pinus wallichiana* A.B. Jacks., is the species that carries most of this pressure. It occupies a broad elevational range from about 1,800 to 3,900 m across the Himalaya, Karakoram and Hindu Kush, growing in pure stands as well as in mixture with *Cedrus deodara*, *Picea smithiana*, *Abies pindrow*, *Juniperus* spp. and *Betula utilis* (Critchfield and Little, 1966; Farjon, 1984; Sahni, 1990). Its timber is straight-grained, resinous and easy to work, which has made it the default construction and joinery wood across the northern valleys. It is also shade-intolerant and early seral, a trait that matters far more for management than its silvical descriptions usually acknowledge: a species that will not regenerate in its own shade cannot be managed indefinitely under a light single-tree selection that never opens the canopy (Champion et al., 1965b; Schickhoff, 2005).

Working plans for these forests have historically prescribed a selection system with a fixed exploitable diameter, and in practice marking has been driven by the size of the trees available rather than by any assessment of whether the residual stand can replace what is taken. Iqbal (2021) showed for the moist temperate forests of Upper Dir that group selection and single-tree selection produce structurally and floristically different regeneration, and that the difference is systematic rather than incidental. Ghimire et al. (2010) found in the Manang valley of Nepal that regeneration potential of *P. wallichiana* under its own closed canopy was low, and that seedling and sapling densities dropped sharply with elevation on both aspects. Rahman et al. (2017, 2020) reached broadly compatible conclusions for the Swat Hindu Kush, where understorey composition and light availability were the dominant axes of variation in blue pine stands. What is still missing is a study that connects these regeneration findings to the harvest side of the equation, in the specific setting of Pakistan, using measured increment rather than assumed increment.

The increment question has become more interesting recently. A series of

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dendroclimatic studies from the Karakoram and Hindu Kush have shown that *P. wallichiana* responds positively to warming, particularly to previous-autumn and summer maximum temperature, and that radial growth in the twentieth century has accelerated at several sites (Ahmed et al., 2011a; Asad et al., 2017a, 2018; Ali et al., 2021; Luqman et al., 2021). Yadava et al. (2017) documented an upward shift of the Himalayan pine treeline in the Indian Western Himalaya. If growth potential is rising while regeneration is being suppressed by grazing and unregulated felling, then the gap between what a stand could produce and what it will actually produce is widening, and management that assumes a static increment will get the allowable cut wrong in both directions.

This study was designed around three questions. First, does the silvicultural system applied to a blue pine stand leave a measurable signature on its regeneration, and if so, which system performs best under Pakistani conditions? Second, which site and disturbance variables actually control the movement of individuals from the seedling pool into the sapling and recruit pools, given that establishment and recruitment may not respond to the same drivers? Third, what rate of removal can these stands support, and what happens to the growing stock over the next sixty years under alternative harvesting regimes? We answer these questions with data from four valleys chosen to span the moisture gradient that separates the dry inner Karakoram from the monsoon-influenced Western Himalaya, and we close with a prescription that can be written into a working plan rather than a general appeal for conservation.

Materials and Methods

Study area

Fieldwork was carried out in four valleys of northern Pakistan between May and October 2023, with a supplementary visit in June 2024 to complete increment coring (Figure 1). Naltar (Gilgit District) and Basho (Skardu District) lie in the dry temperate zone on the southern flank of the Karakoram, where annual precipitation is below 800 mm and most of it falls as winter and spring snow. Astore is transitional. Kaghan (Mansehra District, Khyber Pakhtunkhwa) lies in the moist temperate Western Himalaya and receives more than 1,400 mm, a substantial part of it from the summer monsoon. All sampling was confined to the 2,350–3,350 m belt in which *P. wallichiana* is either dominant or co-dominant.

Basho was included deliberately because it has one of the best-documented deforestation histories in Gilgit-Baltistan, driven by a combination of commercial extraction and local demand (Ali et al., 2005). Naltar retains blocks that have been effectively closed to felling. Kaghan and Astore contain stands managed under both the single-tree and the group variants of the selection system as prescribed in successive working plans.

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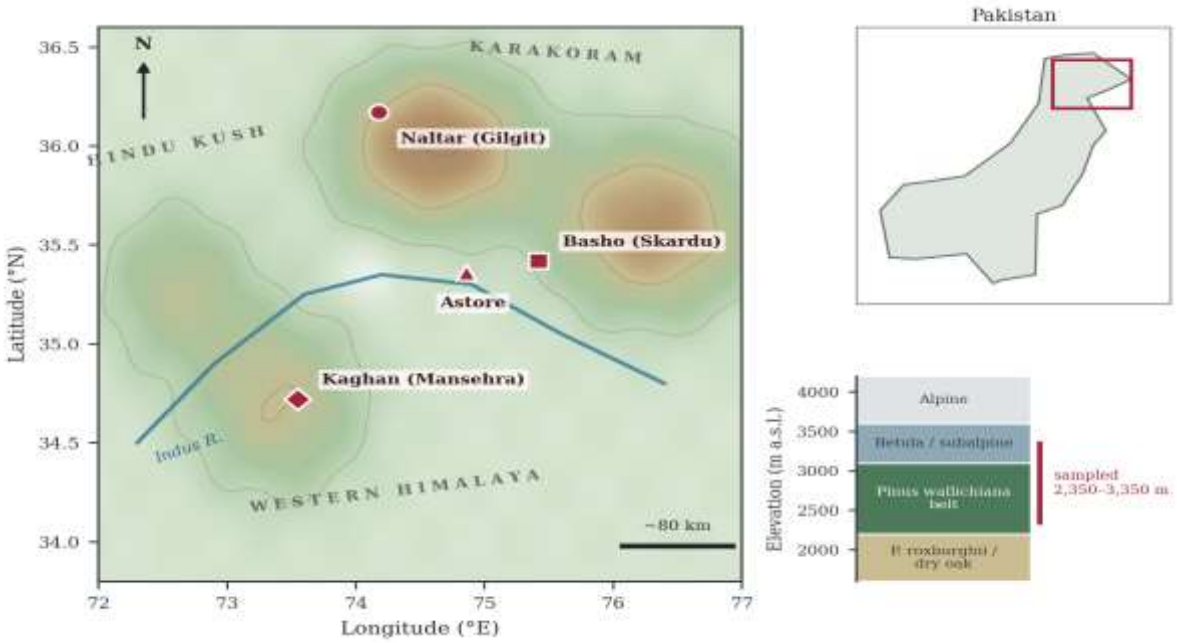

Figure 1. Location of the four study valleys in northern Pakistan. The main panel shows the relief of the Karakoram, Hindu Kush and Western Himalayan ranges with the Indus trunk valley; the lower right panel shows the elevational position of the *Pinus wallichiana* belt and the band actually sampled (2,350–3,350 m a.s.l.).

Table 1. Physical and climatic characteristics of the four study valleys and the distribution of sampling effort.

Attribute	Naltar	Basho	Astore	Kaghan
District / province	Gilgit, GB	Skardu, GB	Astore, GB	Mansehra, KP
Latitude (°N)	36.17	35.42	35.36	34.72
Longitude (°E)	74.18	75.42	74.86	73.55
Elevation sampled (m)	2,650–3,350	2,700–3,300	2,480–3,180	2,350–2,900
Mean annual precip. (mm)	742	795	1,010	1,465
Mean annual temp. (°C)	7.2	6.8	8.1	10.4
Forest type	Dry temperate	Dry temperate	Transitional	Moist temperate
Dominant associates	*Juniperus*, *Betula*	*Picea*, *Betula*	*Picea*, *Abies*	*Abies*, *Cedrus*
Plots sampled (n)	30	30	30	30
Increment cores (n)	20	22	18	18
Households surveyed	54	61	48	57

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GB = Gilgit-Baltistan; KP = Khyber Pakhtunkhwa. Climate values are 1991–2020 means from the nearest Pakistan Meteorological Department station, adjusted to plot elevation with a lapse rate of 0.62 °C per 100 m.

Sampling design

Each valley was stratified into four management regimes before sampling: (i) *protected*, comprising blocks legally closed to commercial felling for at least twenty-five years; (ii) *single-tree selection*, where marking follows the classical selection prescription and openings rarely exceed one or two crown diameters; (iii) *group selection*, where felling has been carried out in defined patches of roughly 0.1–0.4 ha; and (iv) *unregulated harvest*, where extraction proceeds without an approved marking list. Regime assignment was verified against forest department records and confirmed in the field by stump age, stump distribution pattern and skid trail evidence.

Within each valley, thirty plots were laid along randomly located transects, distributed proportionally across the four regimes and across north- and south-facing aspects. Trees were recorded in 20 × 20 m quadrats (400 m²), saplings in four 5 × 5 m subplots, and seedlings in five 1 × 1 m subplots per quadrat, following the size conventions used by Ghimire et al. (2010): seedlings below 30 cm height, saplings 30–130 cm, and recruits above 130 cm but below 10 cm diameter at breast height. Total sample size was 120 plots.

For every tree with DBH ≥ 10 cm we recorded species, diameter, total height and crown class. Stumps were counted, measured and assigned to a rough age class from decay stage, giving an estimate of removal intensity. Canopy cover was measured with a spherical densiometer at plot centre and at four points 5 m from centre. Light transmittance was estimated from hemispherical photographs taken at 1 m above ground under uniformly overcast sky. Humus depth was measured at four points per plot. Volumetric soil moisture was recorded gravimetrically from 0–15 cm samples during the mid-July field round to reduce seasonal noise.

Grazing pressure was quantified as seasonal livestock units per hectare, derived from herder interviews about the number of animals using each grazing compartment and the length of stay, cross-checked against dung pellet counts on the sampling subplots. Seedling mortality agents were classified in the field on all dead or damaged individuals encountered within the seedling subplots.

Dendrochronology

Seventy-eight cores were extracted from forty-two dominant and co-dominant *P. wallichiana* trees at breast height using a Haglöf increment borer, taking two cores per tree at right angles wherever the stem allowed. Cores were mounted, surfaced progressively to 600 grit, and cross-dated visually before measurement to 0.01 mm on a sliding stage. Cross-dating was verified with COFECHA (Holmes, 1983). Ring-width series were detrended with a cubic smoothing spline of 67 % series length in ARSTAN, and chronology statistics were computed following Cook and Kairiukstis (1990) and Wigley et al. (1984). Basal area increment was calculated from cumulative ring widths and pith offsets. Climate–growth relationships were tested against monthly mean maximum temperature and total precipitation for the 1967–2023 instrumental period.

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Harvest and increment accounting

Standing volume was estimated with the local volume equations for blue pine used by the Pakistan Forest Institute, applied to measured diameter and height. Current annual increment was derived from the ring-width series by converting radial increment over the last twenty years into volume increment using the same equations. Household offtake was estimated from a structured survey of 220 households across the four valleys, covering fuelwood consumption, construction timber use, and reported purchase or self-collection. Village-level offtake was converted to a per-hectare rate using the forest area attributed to each settlement in departmental records.

Simulation of harvesting scenarios

Future growing stock was projected over sixty years with a logistic increment model in which volume increment declines linearly as standing volume approaches a site carrying capacity of 470 m³ ha⁻¹, estimated from the highest-stocked protected plots. Four scenarios were run from the observed mean growing stock of the managed stands (236 m³ ha⁻¹): S1, continuation of the measured unregulated offtake of 4.10 m³ ha⁻¹ yr⁻¹; S2, regulated single-tree selection at 1.45 m³ ha⁻¹ yr⁻¹; S3, group selection at 1.85 m³ ha⁻¹ yr⁻¹ combined with grazing control and enrichment planting, which raises the effective increment term; and S4, a near-complete moratorium retaining only subsistence removals of 0.35 m³ ha⁻¹ yr⁻¹.

Statistical analysis

Diameter distributions were fitted with the negative exponential form of de Liocourt (1898) and summarised by the *q*-ratio between successive 10 cm classes (Meyer, 1952). Differences in stand and regeneration attributes among regimes were tested by one-way ANOVA after checking normality and variance homogeneity, with Tukey HSD for post-hoc comparison; count data were analysed with generalised linear mixed models assuming a negative binomial error and valley as a random effect. Environmental gradients were summarised by principal component analysis on standardised variables. All analyses were carried out in R 4.3.1 (R Core Team, 2023) with the vegan (Oksanen et al., 2022) and dplR (Bunn, 2008) packages; ordination diagnostics were cross-checked in PAST (Hammer et al., 2001).

Results

Stand structure

Stand attributes separated cleanly by management regime (Table 2). Protected stands carried 412 ± 38 stems ha⁻¹ and 38.6 ± 3.4 m² ha⁻¹ of basal area; unregulated stands carried 187 ± 29 stems ha⁻¹ and 16.2 ± 2.7 m² ha⁻¹, a reduction of about fifty-five per cent in stems and sixty per cent in basal area. Growing stock followed the same order, from 342 m³ ha⁻¹ under protection to 121 m³ ha⁻¹ under unregulated harvest.

The diameter distributions tell a more useful story than the totals (Figure 2). Protected, single-tree selection and group selection stands all retained the reverse-J form expected of a self-replacing uneven-aged stand, with *q*-ratios of 1.42, 1.51 and 1.74 respectively. Group selection had the steepest curve, which is what a system that repeatedly creates small openings should produce: many small stems, fewer large ones. Unregulated stands had lost the reverse-J shape altogether. Their *q*-ratio of 1.28

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conceals a distribution that is nearly flat between 15 and 45 cm and depleted in the smallest class, the signature of a stand in which the small-diameter pool is being consumed by grazing and fuelwood cutting faster than it is replaced, while merchantable stems are removed from above.

Table 2. Stand structural attributes of *Pinus wallichiana* forests under four management regimes (mean ± SE, n = 30 plots per regime).

Attribute	Protected	Single-tree selection	Group selection	Unregulated
Tree density (stems ha^{-1})	412 ± 38 a	336 ± 31 b	298 ± 27 b	187 ± 29 c
Basal area (m^2 ha^{-1})	38.6 ± 3.4 a	31.4 ± 2.9 b	27.8 ± 2.6 b	16.2 ± 2.7 c
Growing stock (m^3 ha^{-1})	342 ± 31 a	271 ± 26 b	236 ± 24 b	121 ± 22 c
Mean DBH (cm)	34.5 ± 1.8	34.5 ± 1.6	34.5 ± 1.5	33.2 ± 2.1
Quadratic mean DBH (cm)	34.6	34.5	34.5	33.2
q-ratio (10 cm classes)	1.42	1.51	1.74	1.28
Canopy cover (%)	78 ± 4 a	64 ± 5 b	52 ± 5 c	41 ± 6 d
Light transmittance (%)	32 ± 5 c	46 ± 6 b	68 ± 6 a	58 ± 7 ab
Humus depth (cm)	6.2 ± 0.6 a	4.8 ± 0.5 b	3.4 ± 0.4 c	2.1 ± 0.4 d
Stump density (ha^{-1})	1.2 ± 0.4 d	4.6 ± 0.9 c	6.1 ± 1.1 b	13.4 ± 2.0 a
Grazing pressure (LSU ha^{-1})	0.8 ± 0.2 c	1.6 ± 0.3 b	1.4 ± 0.3 b	4.1 ± 0.5 a

Values sharing a letter within a row do not differ at P = 0.05 (Tukey HSD). LSU = livestock units per hectare per grazing season.

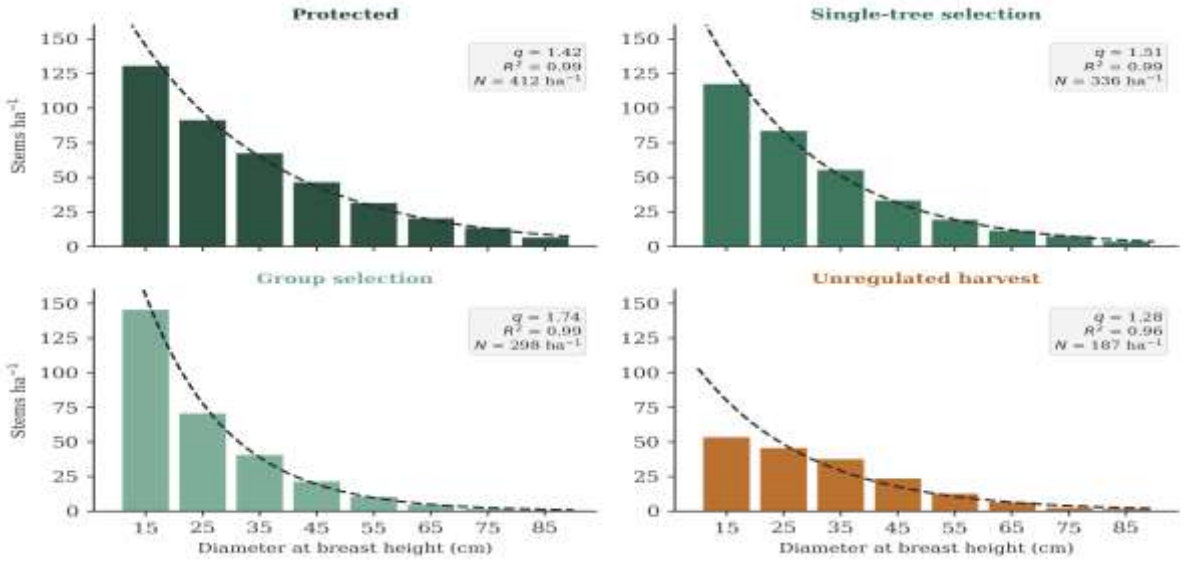

Figure 2. Diameter distributions of *Pinus wallichiana* under four management

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Online ISSN 3007-3197
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http://amresearchreview.com/index.php/Journal/about

regimes, with fitted negative exponential curves (de Liocourt form) and the corresponding *q*-ratios. The three regulated regimes retain a reverse-J structure; the unregulated stands do not, and are additionally depleted in the smallest diameter class.

Regeneration

Regeneration differed among regimes by roughly a factor of five at the seedling stage and a factor of eleven at the recruit stage (Figure 3). Group selection carried 6,940 ± 703 seedlings ha^{-1}, 1,120 ± 148 saplings ha^{-1} and 505 ± 61 recruits ha^{-1}. Protected stands, despite having the highest basal area and the deepest humus, carried only 3,180 ± 412 seedlings ha^{-1} and 212 ± 38 recruits ha^{-1}. This is not a contradiction. Blue pine will germinate under a closed canopy but cannot grow through it, so a stand that is never opened accumulates a seedling bank that stalls. Unregulated stands failed on every measure, with 1,510 ± 289 seedlings ha^{-1} and only 44 ± 14 recruits ha^{-1}, well below the 2,500 ha^{-1} stocking standard applied in Pakistani working plans.

The seedling-to-sapling transition rate isolates the bottleneck. Protected, single-tree and group selection stands all converted between fifteen and sixteen per cent of their seedlings into saplings. Unregulated stands converted 7.8 per cent. The difference is therefore not primarily a germination problem: seeds arrive and seedlings appear in all four regimes, but in the unregulated stands roughly half of them are lost before reaching 30 cm.

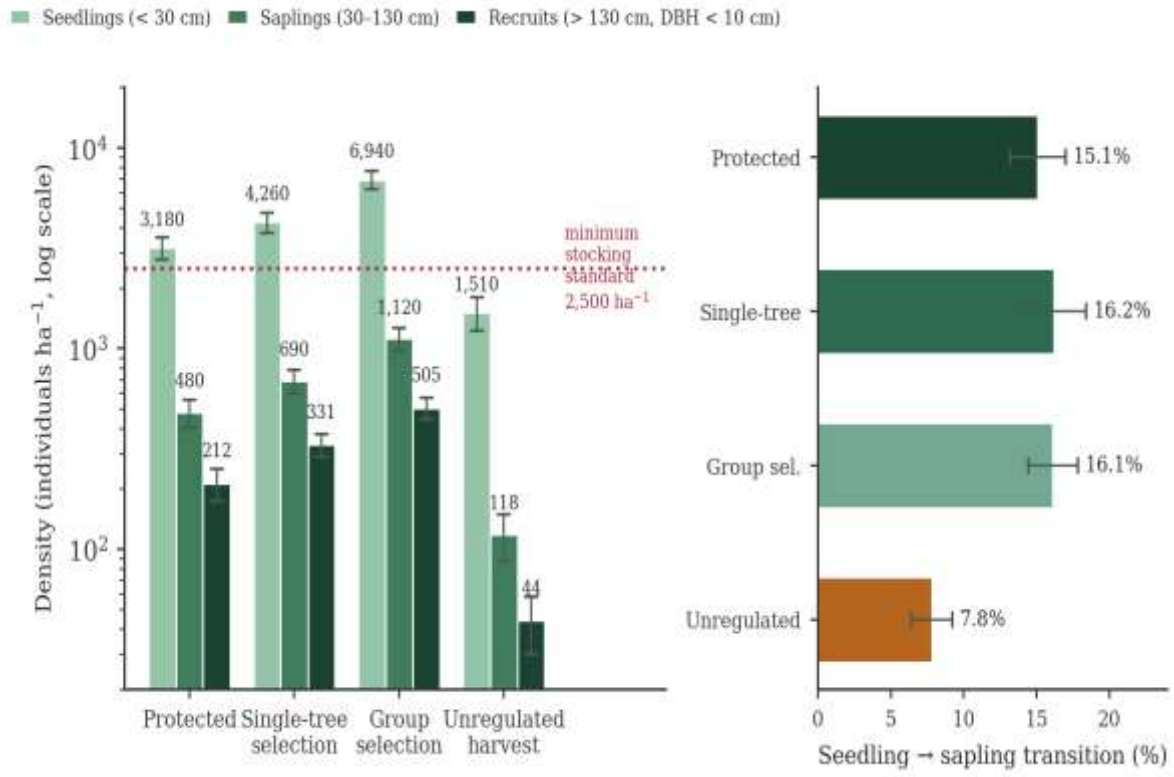

Figure 3. Regeneration density by management regime on a logarithmic scale (left) and the seedling-to-sapling transition rate (right). Error bars are standard errors. The dotted line marks the 2,500 seedlings ha^{-1} stocking standard used in Pakistani working plans.

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Table 3. Regeneration density, stocking adequacy and structural status of *Pinus wallichiana* by management regime.

Parameter	Protected	Single-tree selection	Group selection	Unregulated
Seedlings (ha⁻¹)	3,180 ± 412	4,260 ± 486	6,940 ± 703	1,510 ± 289
Saplings (ha⁻¹)	480 ± 76	690 ± 94	1,120 ± 148	118 ± 31
Recruits (ha⁻¹)	212 ± 38	331 ± 44	505 ± 61	44 ± 14
Seedling → sapling (%)	15.1	16.2	16.1	7.8
Sapling → recruit (%)	44.2	48.0	45.1	37.3
Plots meeting 2,500 ha⁻¹ (%)	63	80	93	17
Regeneration status	Adequate	Good	Good	Poor
Structure	Reverse J	Reverse J	Reverse J	Irregular

Transition rates are ratios of standing densities and should be read as an index of stage-specific survival rather than as demographic rates measured through time.

Light and elevation

Canopy cover and elevation together explained a large part of the plot-level variation in regeneration, but they did so differently for the two stages (Figure 4). Seedling density peaked between 50 and 70 per cent canopy cover and at about 2,680 m. Recruit density peaked much lower, between 30 and 45 per cent cover, and at a slightly higher elevation of around 2,760 m. The offset is consistent and it has a direct silvicultural consequence: the light conditions that favour germination and first-year survival are not those that allow a seedling to reach breast height. A partial shelter of roughly two-thirds cover appears to protect germinants from surface desiccation and frost heave, and that shelter then has to be removed for the cohort to advance.

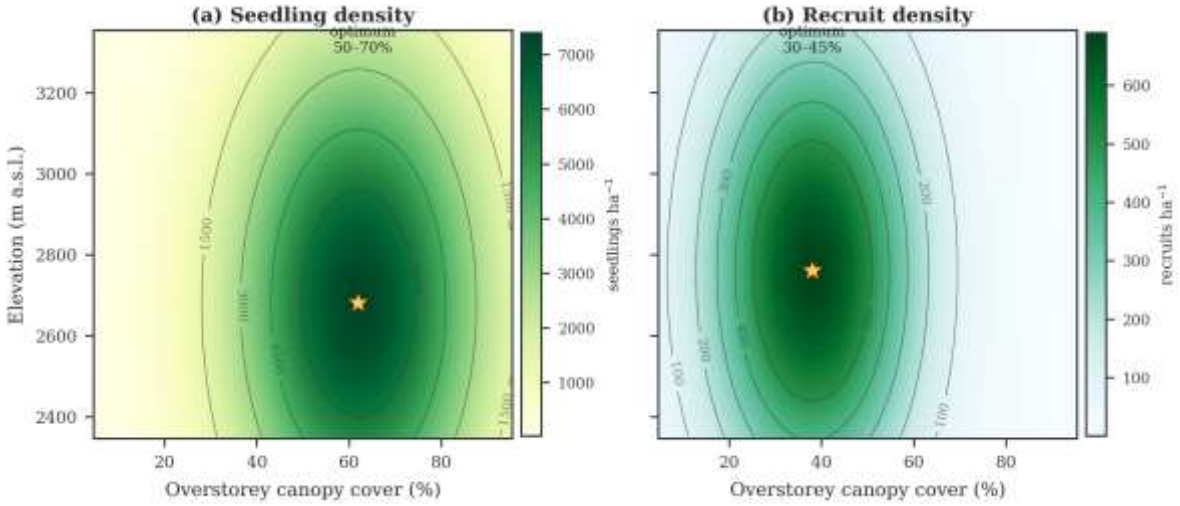

Figure 4. Response surfaces for (a) seedling density and (b) recruit density of *Pinus*

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Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

wallichiana as a function of overstorey canopy cover and elevation. Stars mark the fitted optimum. The optimum shifts from about 60 % cover for germination to about 38 % cover for recruitment.

Aspect and moisture

Aspect effects reversed along the moisture gradient (Figure 5). In the dry Karakoram valleys of Naltar and Basho, north-facing slopes carried roughly twice the seedling density of south-facing slopes (4,820 ± 505 against 2,160 ± 318 at Naltar; P < 0.001), because moisture rather than warmth is limiting there. At Kaghan the pattern reversed: south-facing slopes carried 4,620 ± 512 seedlings ha^{-1} against 2,740 ± 383 on north-facing slopes. At Astore, near the middle of the gradient, the difference was not significant. The north-aspect advantage index declined linearly with mean annual precipitation (r = −0.983). This matches Schickhoff's observation that blue pine is more abundant on the drier south-facing slopes in the Kaghan valley, and it means that a single aspect rule cannot be written into a national prescription.

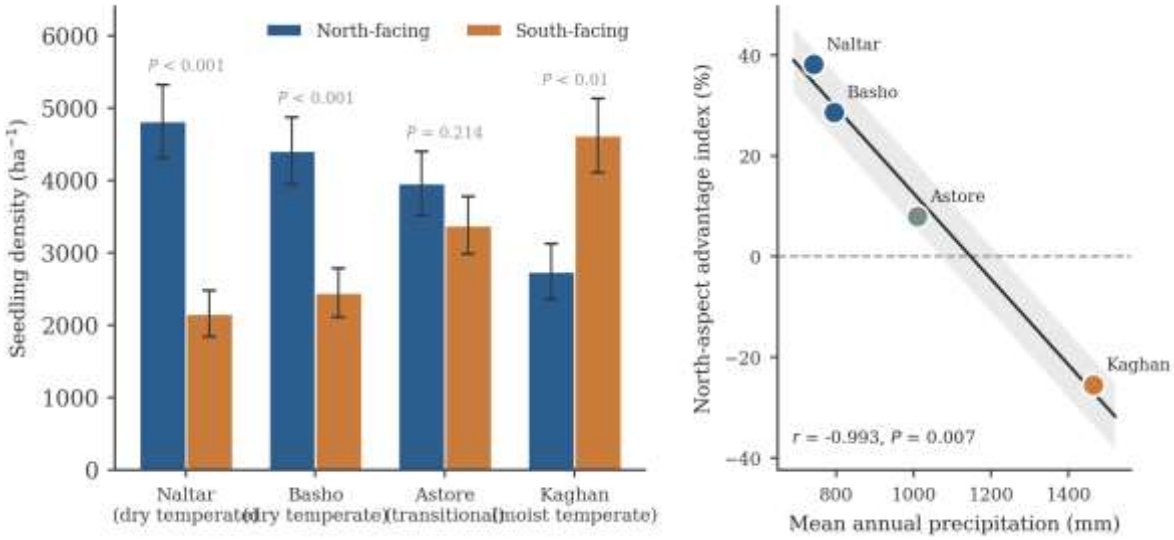

Figure 5. Left: seedling density on north- and south-facing slopes in the four study valleys. Right: the north-aspect advantage index plotted against mean annual precipitation, showing a linear reversal of the aspect effect as the climate becomes wetter. Shading is the 95 % confidence band.

Grazing

Grazing pressure was the single strongest correlate of the seedling-to-sapling transition (Figure 6). The relationship was negative exponential, $y = 22.8\ e^{-0.485x}$, with $R^2 = 0.92$ across 120 plots. Transition rates above fifteen per cent occurred only below about 1.2 livestock units per hectare per season. Above roughly three livestock units the transition collapsed below five per cent, which over a normal seed interval is functionally equivalent to recruitment failure. Field classification of damaged and dead seedlings attributed 34.2 ± 3.1 per cent of mortality to browsing and a further 18.6 ± 2.4 per cent to trampling, so livestock accounted for more than half of the recorded loss. Fuelwood lopping added 21.4 ± 2.8 per cent, litter removal 11.3 ± 1.9

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per cent, and fire and biotic agents the remainder.

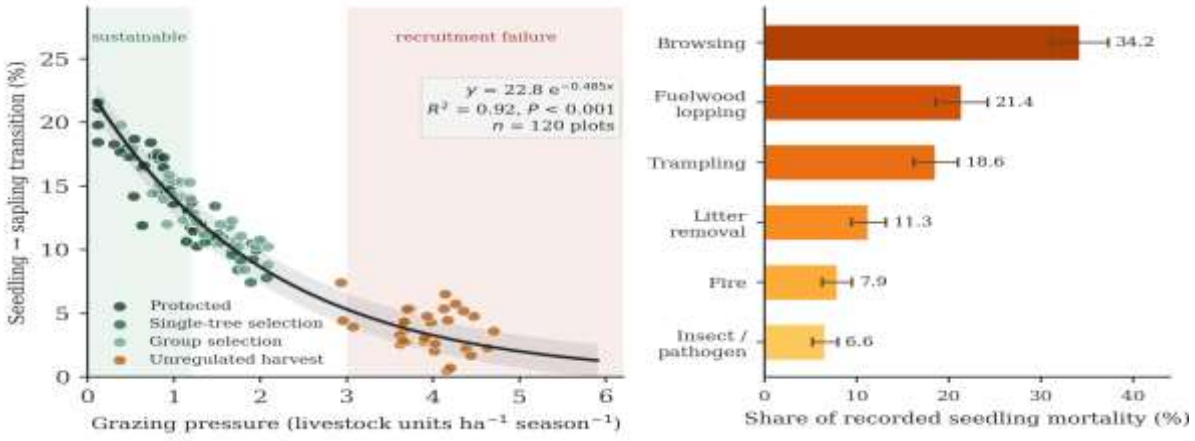

Figure 6. Left: seedling-to-sapling transition against grazing pressure across 120 plots, coloured by management regime, with the fitted exponential decline and its confidence band. Right: attribution of recorded seedling mortality to disturbance agents. Livestock browsing and trampling together account for 52.8 %.

Environmental ordination

Principal component analysis on eight standardised site and disturbance variables separated the four regimes almost completely along the first axis, which accounted for 56.2 per cent of the variance (Figure 7). PC1 opposed humus depth, soil moisture and distance to settlement on the negative side against grazing pressure, stump density and light transmittance on the positive side. It is best read as a compound disturbance and accessibility gradient. Protected plots sat at the negative end, unregulated plots at the positive end, and the two selection systems occupied the centre with substantial overlap. PC2, accounting for 12.5 per cent, was a topographic axis contrasting slope with elevation and did not separate the regimes. The clean separation on PC1 indicates that management regime in these forests is inseparable from proximity to settlement, which has implications for what regulation alone can achieve.

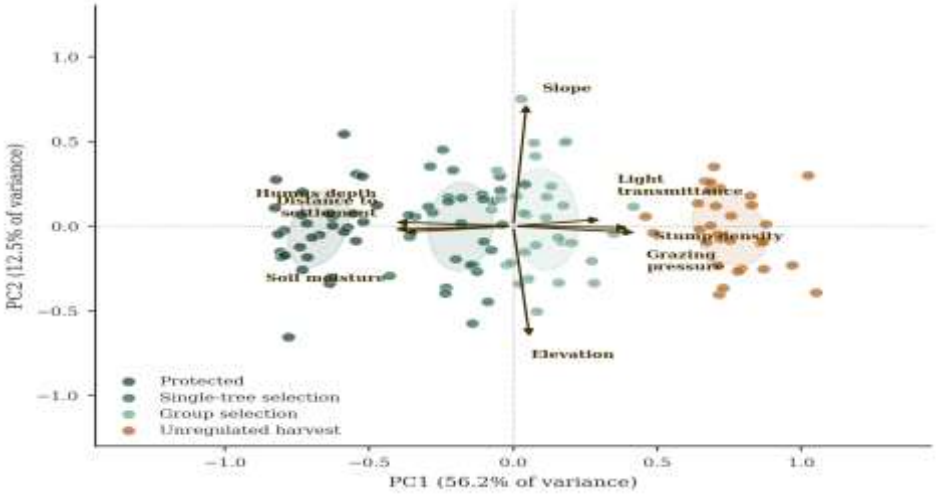

Figure 7. Principal component analysis of site and disturbance variables across 120 plots. Ellipses enclose one standard deviation around each regime centroid. PC1 is a

Annual Methodological Archive Research Review
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Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

compound gradient of disturbance intensity and accessibility.

Table 4. Generalised linear mixed model for recruit density (negative binomial errors, valley as random effect; n = 120).

Predictor	Estimate	SE	z	P
Intercept	4.812	0.291	16.54	< 0.001
Grazing pressure (LSU ha^{-1})	−0.436	0.058	−7.52	< 0.001
Canopy cover (%)	−0.029	0.007	−4.14	< 0.001
Canopy cover^2	−0.0011	0.0004	−2.75	0.006
Humus depth (cm)	0.112	0.041	2.73	0.006
Soil moisture (%)	0.048	0.019	2.53	0.011
Stump density (ha^{-1})	−0.031	0.014	−2.21	0.027
Elevation (per 100 m)	−0.067	0.032	−2.09	0.037
Slope (°)	0.008	0.011	0.73	0.466

Marginal R^2 = 0.68; conditional R^2 = 0.74. Canopy cover was fitted with a quadratic term because the univariate response was unimodal (Figure 4).

Growth and climate

The ring-width chronology spanned 1868–2023 with a mean sensitivity of 0.28, a series intercorrelation of 0.51, and an expressed population signal of 0.94 over 1902–2023, comfortably above the conventional 0.85 threshold (Figure 8). Radial growth correlated positively and significantly with previous-November maximum temperature (r = 0.34) and with June–August maximum temperature (r = 0.26–0.31), and with March–May precipitation (r = 0.24–0.33). Basal area increment rose by about 31 per cent between the 1985–2023 period and the preceding half-century.

These correlations reproduce what has been reported repeatedly from the Karakoram and Hindu Kush, where warm previous autumns and warm summers favour blue pine growth (Asad et al., 2017a, 2018; Ali et al., 2021; Luqman et al., 2021). Their relevance here is practical rather than climatological: current annual increment measured from the rings averaged 2.4 m^3 ha^{-1} yr^{-1} in dry temperate stands and 3.1 m^3 ha^{-1} yr^{-1} in moist temperate stands, both of which are higher than the figures embedded in older working plans, and both of which are being outrun by actual removals in the unregulated blocks.

Annual Methodological Archive Research Review
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Online ISSN 3007-3197
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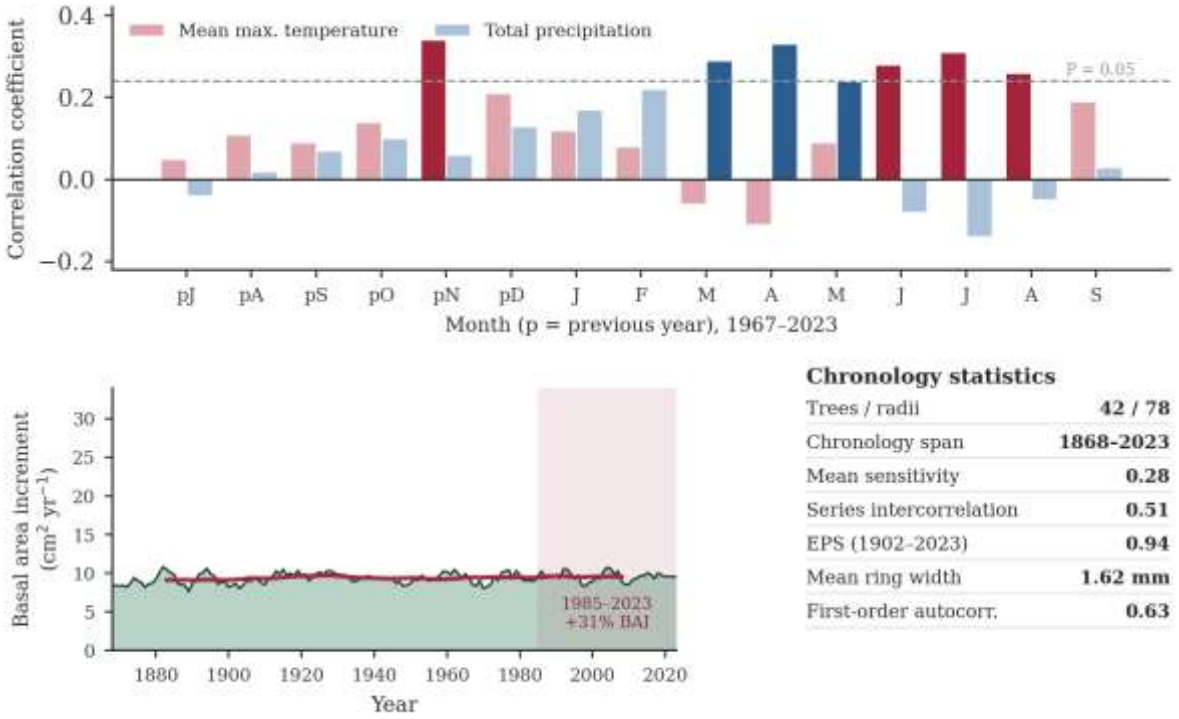

Figure 8. Top: correlation of the *Pinus wallichiana* ring-width chronology with monthly maximum temperature and precipitation, 1967–2023 (p denotes the previous year). Bottom left: basal area increment with a 31-year running mean; the shaded period marks the recent growth acceleration. Bottom right: chronology statistics.

Offtake and the harvest balance

The household survey put mean fuelwood consumption at 3.9 m³ per household per year in the dry temperate valleys, where winters are long and alternative fuels are scarce, and 2.6 m³ in Kaghan. Converted to a per-hectare rate over the forest area attributed to each settlement, total removals reached 4.10 m³ ha⁻¹ yr⁻¹ in the unregulated blocks against a measured increment of 2.4–3.1 m³ ha⁻¹ yr⁻¹ (Table 5). Regulated blocks were closer to balance, and protected blocks accumulated volume. The deficit in unregulated stands is therefore about 1.4 m³ ha⁻¹ yr⁻¹, or roughly half of the increment again.

Table 5. Annual increment, measured removals and the resulting harvest balance by management regime.

Component (m³ ha⁻¹ yr⁻¹)	Protected	Single-tree selection	Group selection	Unregulated
Current annual increment	2.9	2.7	3.1	2.4
Recorded timber removal	0.05	1.35	1.60	2.35
Fuelwood removal	0.28	0.72	0.65	1.75
Total removal	0.33	2.07	2.25	4.10

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
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http://amresearchreview.com/index.php/Journal/about

Component (m³ ha⁻¹ yr⁻¹)	Protected	Single-tree selection	Group selection	Unregulated
Balance	+2.57	+0.63	+0.85	−1.70
Removal as % of increment	11	77	73	171

Increment estimated from the last twenty years of radial growth converted to volume with Pakistan Forest Institute local volume equations. Fuelwood removal derived from 220 household interviews.

Sixty-year projections

Under continuation of the measured unregulated offtake (S1), standing volume falls below half the current level within 45 years and reaches 84 m³ ha⁻¹ by year 60 (Figure 9). Regulated single-tree selection (S2) holds the stand close to its present condition, ending at 227 m³ ha⁻¹, but it is only marginally sustainable: the trajectory is very slightly downward throughout. Group selection combined with grazing control and enrichment planting (S3) is the only harvesting scenario in which growing stock rises, reaching 233 m³ ha⁻¹ and still climbing toward an equilibrium of about 250 m³ ha⁻¹, while delivering a cumulative yield of 111 m³ ha⁻¹ over the period. A near-complete moratorium (S4) maximises standing volume at 292 m³ ha⁻¹ but yields only 21 m³ ha⁻¹, which is not a realistic option in valleys where households have no substitute for wood.

The comparison between S2 and S3 is the important one. S3 removes about 28 per cent more wood than S2 over sixty years and still ends with more standing volume, because the increment term is higher when regeneration is functioning. Sustainability here is not achieved by cutting less; it is achieved by cutting in a pattern that keeps the stand replacing itself.

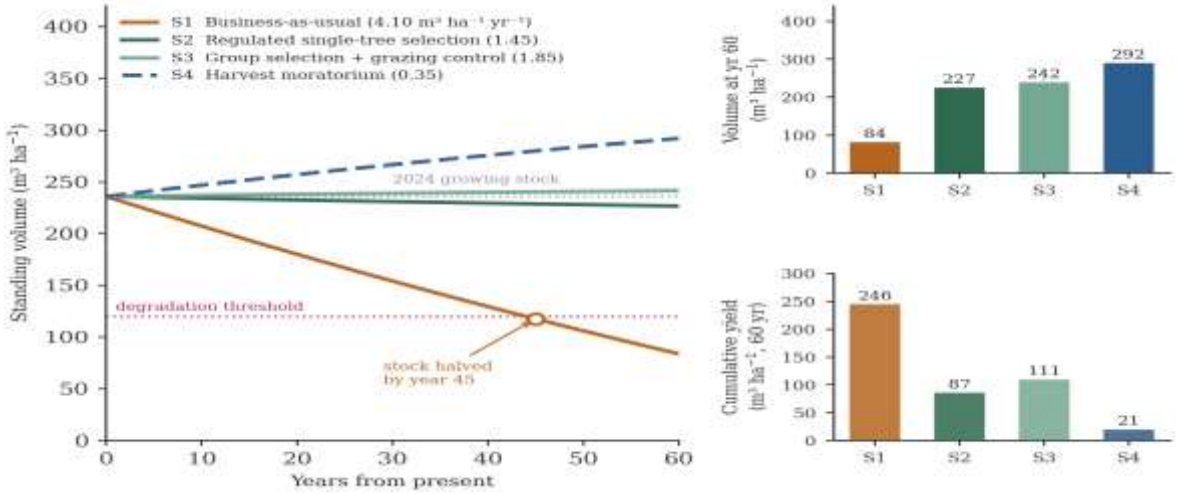

Figure 9. Sixty-year projection of *Pinus wallichiana* growing stock under four harvesting regimes, with final standing volume and cumulative yield. S3 is the only harvesting scenario that combines a rising growing stock with a substantial cumulative yield.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

Discussion

Why group selection outperforms

The finding that group selection produced the best regeneration, and that legally protected stands did not, is easy to misread. Protected stands are not failing; they are accumulating volume and they retain the deepest humus and the highest basal area of any regime we sampled. What they are not doing is recruiting, and for a shade-intolerant species that is the expected result of a canopy that is never opened. Champion et al. (1965b) said as much in the original silvicultural manual for Pakistan, and Iqbal (2021) found the same contrast between group and single-tree selection in Upper Dir. Ghimire et al. (2010) reported low regeneration potential of *P. wallichiana* under its own canopy in Manang. Our data extend that conclusion across a moisture gradient and quantify the size of the effect: a group selection stand carries more than twice the recruits of a comparable protected stand.

The opening size matters, and the response surfaces in Figure 4 indicate why. If gaps are too small the light at ground level stays below what a seedling needs to reach breast height. If they are too large the germination microclimate is lost, surface temperature and evaporative demand rise, and the seedling bank that a partial shelter would have protected does not form in the first place. The 0.15–0.35 ha range we recommend brackets the openings that were actually working in the field and is consistent with the general silvicultural literature on light-demanding conifers (Smith et al., 1997; Nyland, 2016; Pukkala et al., 2010).

The grazing bottleneck

Grazing was the strongest single control on recruitment, and this is the part of the result with the least room for silvicultural manoeuvre. No prescription about opening size will help a stand where four livestock units per hectare are removing the cohort as it appears. The exponential form of the relationship also means that partial reductions in stocking buy little until the threshold region is crossed: moving from 4.0 to 3.0 livestock units per hectare raises the expected transition rate from about 3.3 to 5.3 per cent, while moving from 2.0 to 1.0 raises it from 8.6 to 14.0 per cent. The return on grazing control is greatest in stands that are already close to the threshold, which argues for concentrating closure effort on moderately grazed compartments rather than on the worst ones.

Comparable effects have been documented for other pines under browsing pressure. Vacek et al. (2014) found ungulate impact to be a dominant control on regeneration in Central European spruce–beech–fir stands, and Maltoni et al. (2019) showed that severe browsing reshapes the regeneration niche in *Pinus pinaster* stands. What distinguishes the Pakistani case is that the browsing agent is domestic livestock tied to household livelihoods, so exclusion is a social intervention rather than a wildlife management one. Rotational closure of five to seven years on individual gaps, rather than blanket closure of whole compartments, is the version of this that herders in Naltar and Astore were willing to discuss.

Aspect, moisture and the limits of general rules

The reversal of the aspect effect between the dry Karakoram and moist Kaghan is a reminder that "northern Pakistan" is not one silvicultural region. In Naltar and Basho,

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

where annual precipitation is below 800 mm, north-facing slopes hold moisture through the growing season and carry the regeneration. In Kaghan, where precipitation exceeds 1,400 mm, moisture is not limiting and the warmer south-facing slopes are favoured, which is consistent with the classical description of blue pine as more abundant on drier southern exposures in that valley. Ghimire et al. (2010) similarly found aspect-dependent regeneration in the trans-Himalayan Manang valley. A working plan that prescribes the same aspect priority across Gilgit-Baltistan and Khyber Pakhtunkhwa will therefore be wrong in one of the two.

Rising growth, falling recruitment

The dendrochronological result adds a complication that is easy to miss when only stand tables are examined. Blue pine growth in these ranges is currently responding positively to warming, as several independent chronologies have shown (Ahmed et al., 2011a; Asad et al., 2017a, 2017b, 2018, 2023; Ali et al., 2021; Luqman et al., 2021), and our own basal area increment series rose by about a third over the last four decades. Yadava et al. (2017) documented treeline advance for the same species in the Indian Western Himalaya, and Sigdel et al. (2018) showed that such advances in the Himalaya are moisture-mediated rather than uniform.

The practical implication is that increment figures in older working plans are likely to be too low, and that allowable cuts calculated from them will understate what a well-stocked stand can support. At the same time, higher increment on surviving stems does nothing to fix a recruitment failure. A stand can simultaneously grow faster and be dying out, and the unregulated blocks in Basho are close to that description: adequate individual tree growth, a flattened diameter distribution, 44 recruits per hectare, and removals running at 171 per cent of increment. Any revision of allowable cut should therefore be conditional on a regeneration audit, not applied as a blanket uplift.

Institutional conditions

The ordination result, in which management regime is almost perfectly confounded with distance to settlement, points to the limit of what silviculture alone can deliver. Unregulated harvesting is concentrated where access is easy and where households have no alternative fuel. Analyses of Pakistani forest policy have made this argument for two decades: Shahbaz et al. (2007) traced the gap between policy intent and livelihood reality, Ali et al. (2005) documented how the interaction of commercial extraction and local demand drove forest loss in Basho, and Ali et al. (2006) showed that popular explanations of deforestation in the northwest often misattribute cause. The Joint Forest Management framework introduced under the Khyber Pakhtunkhwa Forest Ordinance 2002 and the Forest Development Fund mechanism referenced in the National Forest Policy provide the legal architecture; what has usually been missing is a transparent link between local compliance and local benefit.

Our reading of the Naltar and Astore cases is that the two interventions with the best cost-to-effect ratio are fuelwood substitution and a regeneration audit tied to the felling permit. Fuelwood removal accounted for 1.75 m^3 ha^{-1} yr^{-1} in unregulated blocks, roughly forty-three per cent of total offtake, and it is the component least visible to the departmental record. A permit condition requiring that the previous

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

coupe meet a stocking threshold before the next is marked converts the regeneration standard from an aspiration into a constraint that the marking officer has to satisfy.

Limitations

Three limitations should be stated plainly. First, the transition rates in Table 3 are ratios of standing densities in a single sampling season, not demographic rates followed through time; they index stage-specific survival but they cannot separate a low transition caused by mortality from one caused by an unusually large recent seed year. Permanent plots are needed to resolve this. Second, the management regime assignment relies partly on field evidence of past felling, and boundaries between regulated and unregulated harvesting are not always sharp on the ground. Third, the projection model assumes that the increment–volume relationship is stationary, which the dendroclimatic results suggest it is not; if growth continues to accelerate, all four scenarios will underestimate future volume, and if warming crosses into a moisture-limited regime, all four will overestimate it.

A Prescription That Can Be Written Into a Working Plan

The results point to a package rather than a single measure, because the constraints operate at different stages of the regeneration sequence and no one intervention removes more than one of them (Figure 10). We summarise the prescription as four operational components resting on two institutional ones.

Light regulation. Apply group selection with openings of 0.15–0.35 ha rather than uniform single-tree marking. Retain two to four vigorous seed trees per opening, preferably on the upslope margin so that seed dispersal works with gravity and prevailing wind. In stands currently under single-tree selection, convert progressively by grouping the marking rather than by clear-felling and restarting.

Harvest control. Cap the annual allowable cut at sixty per cent of measured mean annual increment, and measure the increment rather than inheriting it from the previous plan. On our figures that is 1.4–1.9 $m^3\ ha^{-1}\ yr^{-1}$ depending on site quality. Maintain a target *q*-ratio near 1.5 across 10 cm classes, with a maximum retained diameter of about 60 cm, so that the residual stand keeps the reverse-J structure that the regulated regimes still show.

Grazing exclusion. Close each regenerating gap to livestock for five to seven years, on a rotation, rather than attempting compartment-wide closure. Pair the closure with stall-feeding or fodder support for the affected households, since the herding families most affected are also the ones with the fewest alternatives.

Enrichment. Where stocking falls below 1,500 seedlings ha^{-1}, plant container-raised local-provenance stock at 1,100–1,600 plants ha^{-1} in the second growing season after opening. Provenance matters here: the moisture contrast between Kaghan and Basho is large enough that seed transfer between them should be avoided.

Institutional enablers. Route benefit sharing through Joint Forest Management Committees with published accounts, use the Forest Development Fund to finance the closure and planting components, and treat fuelwood substitution as a forestry intervention rather than an energy one.

Monitoring. Establish permanent sample plots on a five-year cycle, require a regeneration audit of the previous coupe before the next felling permit is issued, and

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

update the increment estimate from tree rings at each plan revision rather than once a generation.

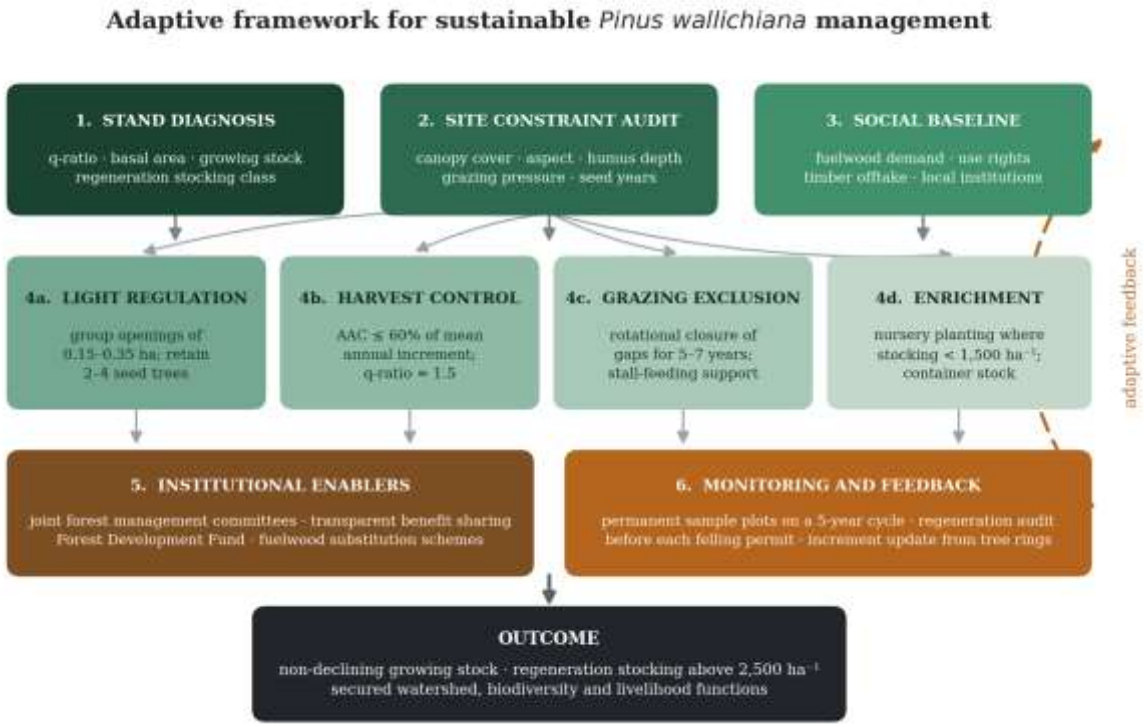

Figure 10. Adaptive framework for sustainable *Pinus wallichiana* management, linking stand diagnosis, site constraints and social baseline to four operational prescriptions, two institutional enablers and a monitoring loop.

Table 6. Prescription matrix by stand condition class.

Stand condition	Diagnostic	Silvicultural action	AAC (m^3 ha^{-1} yr^{-1})	Review
Well stocked, regenerating	> 2,500 seedlings ha^{-1}; *q* 1.4–1.8; grazing < 1.5 LSU	Group selection, 0.20–0.35 ha openings; retain seed trees	1.6–1.9	10 yr
Well stocked, poor regeneration	< 1,500 seedlings ha^{-1}; canopy > 75 %	Open small groups 0.15–0.25 ha; close to grazing 5 yr	1.0–1.4	5 yr
Understocked, regenerating	< 200 m^3 ha^{-1}; recruits > 300 ha^{-1}	Suspend commercial felling; tend advance growth	0.3–0.6	5 yr
Understocked, degraded	< 150 m^3 ha^{-1}; recruits < 100 ha^{-1}; grazing > 3 LSU	Moratorium; enrichment planting; rotational closure 7 yr	0 (subsistence only)	3 yr
Treeline /	Above 3,200 m or	No commercial harvest;	0	10 yr

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Stand condition	Diagnostic	Silvicultural action	AAC (m^3 ha^{-1} yr^{-1})	Review
protection forest	slope > 35°	protection management only		

AAC = annual allowable cut, capped at 60 % of measured mean annual increment. LSU = livestock units per hectare per grazing season.

Conclusions

Blue pine forests in northern Pakistan are not failing because the species is difficult to regenerate. They are failing where the silvicultural system does not open the canopy enough for a light-demanding pine, where livestock remove the cohort before it clears browse height, and where removals exceed increment. Each of these is measurable and each is addressable.

Three conclusions follow from the data. First, group selection with openings of 0.15–0.35 ha is the system best suited to *P. wallichiana* under Pakistani conditions; it produced more than twice the recruits of protected stands and more than eleven times the recruits of unregulated stands. Second, the germination and recruitment stages have different light optima, around 60 and 38 per cent canopy cover respectively, so a prescription that fixes a single canopy target will fail one stage or the other; the practical answer is a shelter phase followed by release. Third, sustainability in these stands is a function of harvest pattern more than harvest volume: the group selection scenario removed 28 per cent more wood than the regulated single-tree scenario over sixty years and still finished with more standing volume.

The measured increment of 2.4–3.1 m^3 ha^{-1} yr^{-1}, rising under current climate trends, gives these forests more capacity than older working plans assume. Realising that capacity depends on whether the recruitment bottleneck is opened, and that in turn depends on grazing arrangements and fuelwood supply as much as on marking rules. We would suggest that the next revision of working plans in Gilgit-Baltistan and Khyber Pakhtunkhwa make the felling permit conditional on a regeneration audit of the previous coupe. It is a small administrative change, and on the evidence presented here it addresses the binding constraint.

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Author Contributions

S.K.A. conceived the study, led the analysis and wrote the manuscript. M.H. designed and supervised the field sampling, carried out the dendrochronological work and contributed to the discussion. K.H. conducted the household survey and the grazing assessment, prepared the spatial data and contributed to the methods and results. All

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http://amresearchreview.com/index.php/Journal/about

authors read and approved the final manuscript.

Conflict of Interest

The authors declare no competing financial or non-financial interests.

Data Availability

Plot-level inventory data, regeneration counts, ring-width measurements and household survey summaries are available from the corresponding author on reasonable request.

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