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Vegetation Pattern and Regeneration Dynamics of the Progressively Declining *Monotheca buxifolia* Forests in Pakistan: Implications for Conservation

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Abstract: *Monotheca buxifolia* (Falc.) A. DC., a wild edible fruit-yielding tree species, has economic and ecological importance, yet there is a lack of studies concerning its distribution pattern and regeneration dynamics at a larger-scale. This study aims to produce the first country-level classification of *Monotheca* forests based on their unique floristic composition and influential abiotic factors, besides their natural regeneration dynamics, across the environmentally diverse landscapes in Pakistan. For this purpose, floristic inventory was carried out in 440 plots where environmental variables, stand dendrometric characteristics and woody-species regeneration were recorded. During this survey, 3789 individuals of 27 woody tree species belonging to 25 genera and 22 families were sampled. These native and exotic tree species were mostly dicot (73%) with predominately mega-phanerophytic (88%) lifeforms, which largely reflect strong chorological differentiation and distinct linkage (55%) to the Sino-Japanese phytogeographical region. *M. buxifolia* and co-occurring species exhibiting similar environmental affinities were grouped into four ecologically distinct communities by Ward's cluster analysis. Ordinations further highlight the special effects of topographic and edaphic factors besides anthropogenic interference on the sampled plots. Generally, *Monotheca* stands were moderately dense, with the average density varying considerably, ranging from 296 to 325 individuals/ha, with basal area ranging from 41.26 to 93.35 m^2 ha^{-1}. In the understory stratum, natural regeneration of *Monotheca* was mostly scant and mainly covered by *Dodonaea* shrubs. Size class structure of the dominant species shows pronounced effect of anthropogenic intervention as reflected by the presence of fewer individuals of juveniles and larger trees. Overall, the cut stump frequency was higher at juvenile and mature stages, which may be attributed to over-harvesting and extraction of fuelwood apart from the adverse effect of climate change in the region. We concluded that both topographic and edaphic factors coupled with biotic interventions are more influential in the distribution and persistence of *M. buxifolia* and co-occurring woody species and might be considered in its restoration and conservation. Thus, we recommend an urgent management plan to favor *Monotheca* regeneration for allowing the renewal of these rapidly declining remnant stands in Pakistan.

Keywords: vegetation dynamics; *Monotheca* regeneration; species diversity; forest conservation

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1. Introduction

Ecosystem dynamics are mainly determined by biological resources, specifically natural vegetation where floristic and faunistic life are present [1]. Environmental conditions, spatial heterogeneity, and disturbances all play significant roles in plant community composition, species persistence, and plant richness [2]. In forest systems, vegetation composition is also the result of complex and mutual relationships between the overstory and the understory, although the influence of the overstory is determinant as it controls the availability of resources on the forest floor [3–5]. Likewise, understory vegetation is particularly important to forest regeneration because it can affect the germination, survival, and growth of tree seedlings [6] or by allelopathic effects [7]. Various studies have confirmed that the species composition and diversity of understory flora can be influenced by canopy species [8], stand management [9], ground disturbances [10], light resources [4,5], litter properties, soil nutrients and pH [11]. Different environmental, biotic and human interventions highly influence the spatial distribution of plant species [12]. Species distribution and diversity reflects the effects of altitude [2,13] and slope gradients [14]. Similarly, edaphic factors are declared to be the most overriding factors responsible for distribution patterns [1,15], of which the most prominent are soil nitrogen and carbon contents, soil texture, and available nutrients [16]. In addition, several authors confirmed that human-caused and natural hazards are also among the well-known elements that have significant impacts on the structure, composition, and function of forest ecosystems [17].

The existence of a plant community is also highly related to its regeneration potential under different environmental conditions, which means that long-term sustainability of a forest depends on successful regeneration [18]. In fact, regeneration and particular habitat conditions determine the future species composition and geographical distribution in a forest [19]. In addition, regeneration capacity often determines the resilience of the ecosystem and its capacity for recovery after a disturbance [20]. A sufficient quantity of seedlings, saplings, and trees for a species in a forest is required to recover successfully depending on the structure and habitat characteristics of the forest [21]. Overstory and the spatial repartition of dominant trees have a direct effect on natural regeneration as well as soil surface conditions [22].

Life form characterizes several adaptive features of a species, and thus it is an agreement to the environmental condition of a plant [23]. The life form reflects the adaptation of plants to the climate of a region. The relative proportion of different life-forms for a given region is sometimes called its bio-spectrum as well [24]. Until now, several procedures have been adopted to classify plant life-forms, in which Raunkiaer's [25] system is more acceptable. The floristic composition of various life-forms and leaf sizes help to access the plant wealth, its potentiality in a given area, and accepting the basic aspects of biology such as isolation, speciation, evolution and endemism [26]. A signal for micro and macroclimate is supposed to be the life-form spectra, and this explains major and minor disturbances of vegetation in a specific area.

M. buxifolia is a wild fruit-yielding tree species which is highly restricted in its distribution across the globe and mainly reported from some mountains of Afghanistan, Oman, Saudi Arabia, and Hindukush and Suleiman mountain ranges of Pakistan [27]. This tree species is reported as either pure crop, or growing in association with other broadleaved tree species like *Olea ferruginea*, *Quercus baloot*, *Dalbergia sissoo*, *Ficus palmata* and *Punica granatum* [28]. *M. buxifolia* provides a variety of ecosystem services like timber, fodder, sheltering and also yields wild fruit called "Gurgura", which is nutritionally rich and also an income source for mountain inhabitants. Medicinally the fruit is laxative, digestive, and is used in treating urinary tract diseases [29]. The hard nature of the *Monotheca* timber allows its usage for different agriculture practices, firewood and other household needs [28].

Northern areas of Pakistan i.e., particularly Hindukush mountains, are considered a hub of biodiversity, contributing 2400 species to the total 6000 reported species across the country [30]. Both broadleaved plants and conifers are the major contributors and are being rapidly reduced mainly due to anthropogenic factors reported by various environmentalists, ecologists and foresters [31,32]. In Pakistan, few ecological studies have been conducted on broadleaved tree species, e.g., *O. ferruginea* [2,32], *P. granatum* [33], *A. modesta* [34], *A. senegal* [35], dry-oaks [36], subtropical dry deciduous forests in district Sawabi [27], dry and moist temperate coniferous and mixed broadleaved species [31] etc. However, very little attention was paid to describing species composition, dominance, diversity, richness and regeneration capacity in *Monotheca* forests. Keeping in view, the current study was designed to accomplish the following: (a) to characterize the *Monotheca* forests in terms of forests structure, floristic composition, and species diversity in relation to main environmental and edaphic variables; (b) to analyse more specifically the *Monotheca* natural regeneration capacity across the environmentally diverse landscapes in Pakistan.

2. Materials and Methods

2.1. Study Area

Vegetation composition and natural regeneration potential of *M. buxifolia* in its natural habitats were analyzed across Pakistan from 2018 to 2019 (Figure 1). Pakistan is located in South Asia covering an area of 80,943 km^2, positioned from 60°55′ to 75°30′ of east longitude and 23°45′ to 36°50′ of north latitude [27]. It has a diverse climate and unique biodiversity with 6000 known plant species due to the large altitudinal gradient, i.e., from sea-level to 8611 m [16]. A large number of hotspot areas along the elevation gradient have also been explored starting from mangroves to alpine pasture. These areas harbor about 10% of the endemic plant species in Pakistan. The hotspot flora of the studied area is scattered in 13 natural regions, where the endangered flora is >10% [27]. Pakistan has four distinct seasons, and the temperature varies both seasonally and regionally; the southern part has a hot and dry climate, whereas the northwest has a temperate climate and the northern part is arctic. Variability in the temperature has been observed and ranged from −22 °C to 50 °C at northern and southern parts, respectively [37]. Similarly, the annual precipitation in the north of the country ranges from 1500 to 2000 mm, while in the south it ranges from 100 to 200 mm [38]. Pakistan is also facing the brunt of climate change due to which shrinkage in hydrological reserves, glaciers melting, heavy floods, and droughts are predicated, which can affect the vegetation in the area.

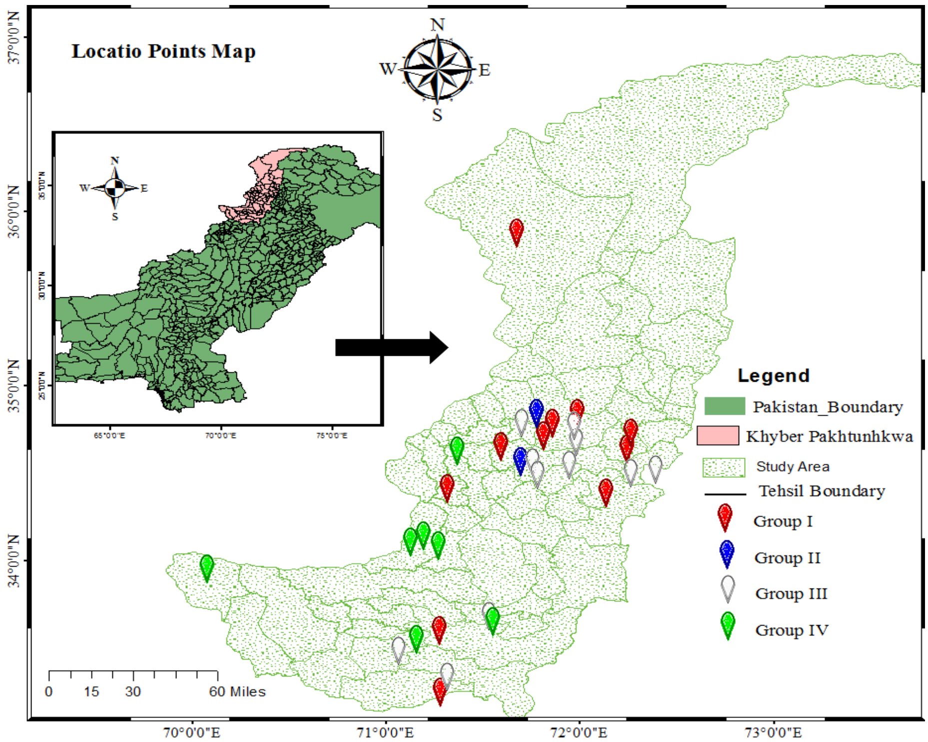

Figure 1. Map displays forests stands across the elevation gradient in Pakistan. Vegetation types resulted in Ward's classification are presented in different colors.

2.2. Sampling Design Data Collection

After going through a review of literature and general survey, 44 least disturbed *M. buxifolia* dominated forests spreads on more than 1 hectare area were selected for sampling [16,32]. Because most of the woodlands in Pakistan have been exposed to some degree of disturbances (i.e., grazing, intense logging, or fire), consequently we looked for evidences of human activities. In particular, we recorded the presence or absences of terraces, agricultural practices, cutting in the overstory and clearing of shrubs in the understory vegetation stratum [1]. The phytosociological data were systematically collected by establishing 10 quadrates of 20 m × 20 m for woody tree species and 5 m × 5 m plots for understory in representative ecological conditions [27,39].

2.3. Measurements

2.3.1. Floristic Composition

Various ecological parameters like species trunk diameter at breast height (DBH) and height for individual trees within a plot were recorded. DBH was measured with a diameter tape, while height (m) was measured by a telescopic Hastings fiberglass rod (H < 15 m) and Abneys level. Multi-stem phenomenon was common in *M. buxifolia*; therefore, the diameter of multi-stemmed trees were calculated following standard methods [40]. Likewise, specimens of the understory and canopy vegetation were collected and identified with the help of taxonomists following Flora of Pakistan.

2.3.2. Environmental Factors

Prior of collecting the vegetation data, different parameters like slope angle, aspect, altitude and geographical coordinators in each plot were recorded using GPS and clinometer [33]. Soil samples were collected from all sampled plots using rings of stainless steel, packed in polythene bags and transported to the Swat Agriculture Research Institute (SARI) for physiochemical analysis. These sampled soils were allowed to air-dry and sieved (2 mm) to remove woody detritus and eroded stones [27]. Different soil parameters such as pH, soil texture, organic matter, nitrogen (N), potassium (K), phosphorus (*p*), water holding capacity (WHC), electrical conductivity (EC), total dissolve solutes (TDS) and soil bulk density (BD) were assessed [41,42].

2.3.3. Regeneration Measurement

For regeneration profile, individuals of *M. buxifolia* in each sampled plot were measured, counted and pooled into five different diameter classes. Newly germinated plants having heights less than 3 cm were counted as seedlings followed by saplings (height = 3 ≥ 5 cm) as suggested by Khan et al. [32,40] and Rigg et al. [43]. Plants having trunk DBH between 5 and 30 cm were pooled in small trees, DBHs 31 to 55 cm in medium trees, 56 to 80 cm in large trees, while individuals having DBHs greater than 80 cm were considered as mature trees. The number of individuals of dominant species in different diameter classes was utilized as a substitute of age classes in static life tables as suggested by Khan et al. [32]. The rate of survivability, mortality and killing power were calculated for the dominant species only due to scarce appearance and low density of the associated species.

2.4. Data Analysis

Brief description such as family name, local name, chorology, life-forms and leaf spectra of individual tree type were recorded and analyzed using the literature. The phytosociological characteristics and absolute values were summarized following Muller-Dombois and Ellenberg [44]. Importance values for individual tree species were calculated and then subjected to PC-ORD package (6.1) for performing multivariate analysis, i.e., classification by choosing Ward's agglomerative techniques [2]. Here we joined Sorensen (Bray–Curtis), an effective distance measure and flexible beta as linkage method (($\beta = -0.25$), which are more compatible and space-conserving [45]. The floristic array comprised of 44 stands × 27 species and an array of environmental factors (44 stands × 20 factors) were prepared and then analysed using RDA-ordination to explore the pattern of sampled forests and their relationships to environmental attributes [46]. RDA is a linear model and is the best suited ordination method in exposing the relation between species composition and environmental variables [47,48]. We performed Monte Carlo permutation test (499-iterations) to assess the significance of the RDA eigenvalues associated with the first axis. Likewise, the importance of each environmental factor was computed using intra-set correlations. Variation in phytosociological attributes, absolute values, species richness and diversity indices among the resulted vegetation groups were analysed using analysis of variance (one-way ANOVA) to determine any statistically significant differences between the means. Because ANOVA is an omnibus test statistic, Tukey's HSD test was used as a post hoc test for determining specific group differences [27].

For regeneration, we constructed Static Life Tables using diameter data as alternative of age classes for *M. buxifolia* at community levels (Group-level). Because many of the broadleaved trees did not produce visible annual growth rings, calculating exact age was not possible. Generally, life tables are prerequisite in studying the population dynamics [49]; however, it did not trace entire cohort life history starting from birth to death but displayed precise time among age-dynamics sequence of multi-generation overlap [50]. Here we gained static life tables by a series of equations as *Ax* is the survival number in diameter class X after smooth out, lx is the static survival number standardized to 1000 (lx = ax/a0 × 1000), dx is the death number from age class X to x + 1 (dx = lx − lx + 1), qx is the mortality from age class X to x + 1 (qx = dx/lx × 100%), kx is the killing factor from class to class x + 1 (kx= log10 lx − log10 l x + 1), Lx is the still alive number of the individual from age-class X to age-class x + 1 (Lx = (lx + lx + 1)/2), Tx is the total number from age-class X to over-age class (Tx = Σ *Lx*) and *ex* is the life-expectancy at age X ($ex = Tx/lx$), respectively. Life tables, survival and mortality curves were prepared for all 44 sampled forests and also for 4 community types individually and are presented in the form of graphs.

3. Results

3.1. Floristic Composition

Overall, we recorded 86 plant species of which 27 were distributed in tree stratum (≤05 DBH), belonging to 25 genera of 22 families (Table S1). Based on species occurrence, the most abundant families were Moraceae and Mimosaceae contributing three species each, followed by family Pinaceae (two species). The remaining 18 families were represented by one species each. Members of these families represent most of the floristic structure in the broadleaved and conifers forests of Pakistan in different localities. The recorded woody trees species were comprised of conifers (11.11%) and broadleaved plants (88.89%), of which 59.26% were deciduous and 29.63% were evergreen tree species. Only 7.41% of the recorded species belong to gymnosperms, while 92.59% fall in the category of angiosperms. Dicot were represented as 88.89%, whereas only 11% were monocot species in overstory stratum (Table S2). In the understory stratum, we found 59 species belonging to 30 families comprised of shrubs (55.9%), herbs (37.28%), and grasses (6.77%). Lamiaceae and Asteraceae were the most diversified families contributing six species each followed by Solanaceae (five species) Poaceae and Apocynaceae (four species each) on the forest ground floor.

3.2. Chorological Affinities and Life-Forms

The chorological affinities in tree stratum revealed that 36.67% of the total species were bi-regional followed by pluri-regional (33.33%) and uni-regional (30%) with 7.40% exotic species. About 23.08% of the total surveyed species were native to Iranian-Turanian region, whereas 15.38% extend their distribution to Euro-Siberian phytogeographical region. Overall, the Sino-Japanese region accounts for 55% of the flora, making it the most important component of this study's floristic makeup (Table S2). The life-form spectrum shows that 19 species belonged to megaphanerophytes (88.89%) followed by nanophanerophytes (3 species). Similarly, microphyll was the leading leaf-size class spectrum (nine species) followed by mesophyll (seven species), leptophyll (six species) and naoaphyllous (four species) respectively (Table S2).

3.3. Communities–Environment Relationships

The effect of 20 different topographic and edaphic variables on the distribution arrangements of woody flora was analyzed RDA (Figure 2). The eigenvalues of RDA are presented in Table 1, whereas correlation with environmental variables and biplot scores are shown in Table S3.

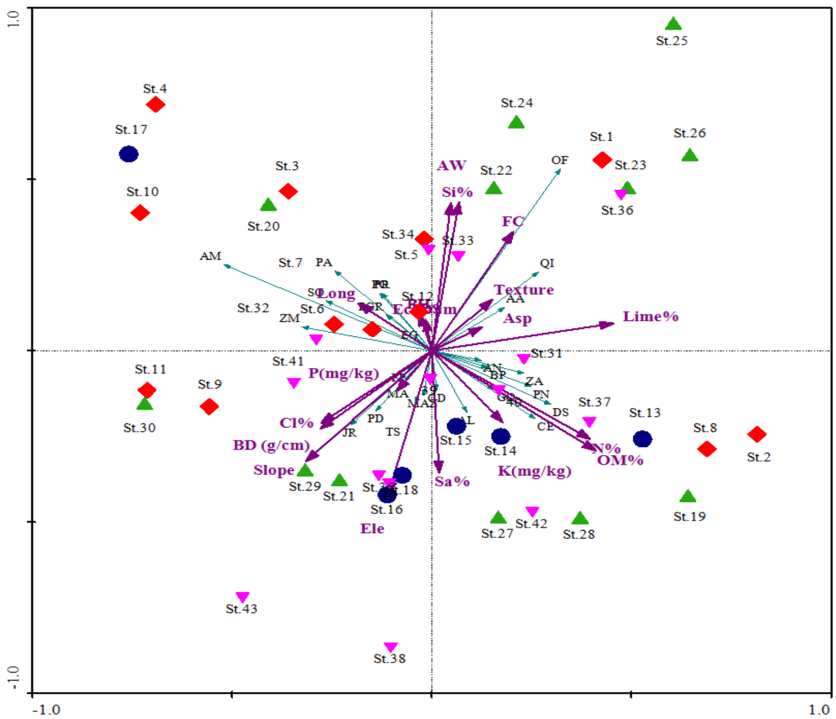

Figure 2. RDA-biplot of 44 *Monotheca buxifolia* forests and 20 corresponding environmental variables. Species and environmental factors acronyms details are given in Tables S1 and S2, respectively. Colors represent four different vegetation types, i.e., red color = *Mono-Acacia*, pink color = *Mono-Olea*, blue color = *Mono-Eucal*, and green color = pure *Monotheca* crop.

Table 1. Eigenvalues extracted from RDA axes using 44 vegetation plots and 20 driving factors.

	Axis 1	Axis 2	Axis 3	*p*-Value
Eigenvalue	2.85	1.613	1.411	0.025
% of variance explained	10.6	6.0	5.2	-
Cumulative % explained	10.6	16.5	21.8	-
Pearson Correlation, Spp-Envt	0.893	0.902	0.896	0.118
Kendall (Rank) Corr., Spp-Envt	0.5	0.61	0.636	-

Monte Carlo test permutation of RDA showed significant interaction between the matrices (i.e., p =0.025 and 0.118) for eigenvalues and species–environment, respectively. The first three axes explained 21.8% of the variability in species data, for which 10.6% were accounted in the first axis. The results explain significant correlation (0.902, p = 0.118) between species and environmental factors in the second axis of RDA. In general, RDA exposed the pattern of species composition along different environmental variables, such as clay, and texture among the physiographic variables produced, showing negative and positive correlations with canonical axis 2, whereas Lime (%) and Nitrogen (%) exhibited positive correlations with axis 3. The results of redundancy analysis suggested that no variables show significant correlation with axis 1. The biplot species data (Table S3) shows that *G. optiva, J. regia, M. azedarach, A. modesta, p. nigra, A. nilotica* and *F. palmata* have greater loading on the axes and occupied the negative end of Axis 1. *A. lebeck*, *C. decidua*, *Z. muratiana* and *S. oleoides* occupied the upper portion at positive ends. Species such as *A. modesta*, *O. ferruginea*, *p. granatum* and *M. azedarach* were companions and grouped together under the similar environmental conditions. These species clustered in the upper middle of the ordination continuum (RDA-biplot) (Figure 2), showing strong relation under similar environmental conditions.

3.4. Description of the Ecological Species Groups

Based on importance value index (IVI), we classified 27 woody tree species into 4 different communities (i.e., *Mono-Acacia*, *Mono-Olea*, *Mono-Eucal* and pure *Monotheca*) using Ward's agglomerative clustering techniques (Figure 3, Figure S2). The first community was dominated by *M. buxifolia* and *A. modesta*, which were recorded from 12 sites located at different altitudes (mean of 1038.03 ± 68.8 m) and on gentle slopes (21.08° ± 2.85). A total of 853 individuals in this group belong to 23 species which ranked this group as the richest one among all the communities (Table 2). This community is characterized by a high amount of silt and a lesser amount of sand. Soil of this group was deficient of organic matter, lime, nitrogen, phosphorus and potassium contents. Other associates of this group were *A. altissima*, *P. roxburghii*, *P. granatum*, *D. sissoo*, *Z. mauritiana*, *M. azedarach* etc. (Table 3).

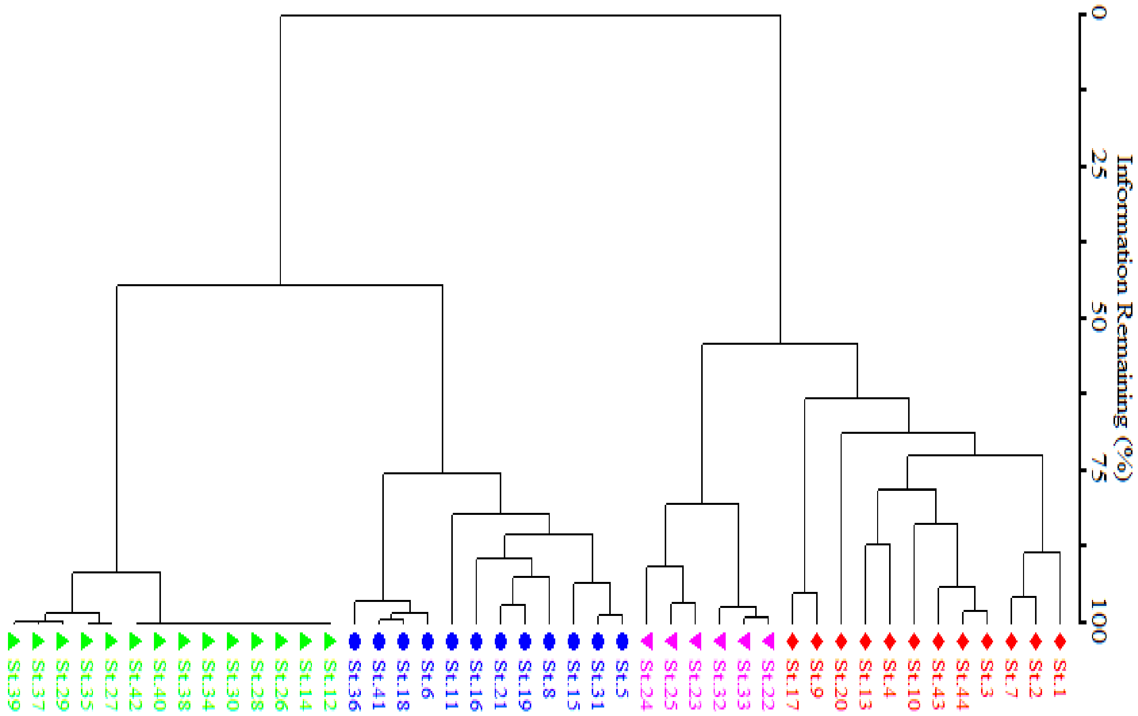

Figure 3. Dendrogram obtained from Ward's cluster analysis of 44 stands and 27 woody tree species surveyed in different regions of Pakistan. Colors representing four different vegetation types are given in Figure 2.

Table 2. Species richness and diversity indices for the four *Monotheca* dominated communities.

	Group-I Mono-Acacia	Group-II Mono-Olea	Group-III Mono-Eugl	Group-IV Mono	F	*P*
Richness	23 [a] (4.08 ± 0.59)	09 [b] (3.33 ± 0.95)	17 [c] (4.08 ± 0.89)	07 [b] (3.43 ± 0.57)	0.286	0.834
Average no of individuals	72.75 ± 3.2	68.5 ± 5.7	80.3 ± 5.76	72.78 ± 5.85	0.718	0.546
Total no of individuals	853	411	964	1019	×	×
Margalef's Index	0.71 ± 0.13	0.54 ± 0.21	0.68 ± 0.19	0.56 ± 0.12	0.25	0.856
Simpson's Index	1.45 ± 0.15	1.38 ± 0.19	1.57 ± 0.17	1.49 ± 0.11	0.228	0.875
Shannon-Wiener Index	0.62 ± 0.09	0.52 ± 0.25	0.68 ± 0.13	0.55 ± 0.09	0.290	0.832
Pielou's Index	0.46 ± 0.05	0.29 ± 0.11	0.49 ± 0.06	0.48 ± 0.06	1.102	0.359

Note: Different letter in the superscript means significant variations between the mean at $p < 0.05$, tested by post hoc Tukey HSD.

Table 3. Phytosociological characteristics of tree vegetation based on agglomerative clustering procedure. Mean (±SE) values were computed in the analysis and one-way ANOVA following Tukey HSD test were performed form comparison. Species acronyms details are given in Table S1.

Acroyms	Mono-Acacia	Mono-Olea	Mono-Eugl	Mono	F-Value	*p*-Value
Mobu	**59.38 ± 1.6 [a]**	**69.22 ± 2.44 [b]**	**80.88 ± 1.29 [c]**	**97.49 ± 0.97 [d]**	143.61	1.89×10^{-21}
Eugl	0.72 ± 0.4 [a]	0 ± 0 [a]	**3.83 ± 1.49 [b]**	0 ± 0 [a]	42.219	0.002
Quba	1.44 ± 1.19	0 ± 0	0 ± 0	0 ± 0	1.305	0.285
Ceeu	1.56 ± 1.28	0 ± 0	0.87 ± 0.59	0 ± 0	1.923	0.141
Aial	4.78 ± 1.5 [a]	0.39 ± 0.39 [b]	0.77 ± 0.77 [b]	0 ± 0 [b]	6.120	0.0015
Moal	1.89 ± 0.71	1.87 ± 1.34	0.61 ± 0.61	0.36 ± 0.36	1.483	0.233
Fipa	1.17 ± 0.54	1.4 ± 0.91	1.1 ± 0.75	0.27 ± 0.27	0.731	0.539
Olfe	2.61 ± 0.69 [a]	**19.58 ± 3.3 [b]**	1.51 ± 1.02 [c]	0.34 ± 0.34 [c]	42.377	1.72×10^{-12}
Meaz	1.26 ± 0.63	0.77 ± 0.77	0 ± 0	0 ± 0	2.608	0.064
Brpa	0.43 ± 0.30	0 ± 0	0 ± 0	0 ± 0	1.807	0.161
Piro	3.01 ± 2.21	0 ± 0	0 ± 0	0 ± 0	1.631	0.197
Dasi	1.59 ± 1.08	0 ± 0	0.27 ± 0.27	0 ± 0	1.563	0.213
Zaar	0.44 ± 0.31	0 ± 0	0 ± 0	0 ± 0	1.780	0.166
Pige	0.25 ± 0.25	0 ± 0	0 ± 0	0 ± 0	0.881	0.458
Acmo	**11.35 ± 3.43 [a]**	4.89 ± 1.95 [b]	2.69 ± 1.53 [b]	0 ± 0 [c]	5.776	0.002
Pugr	2.55 ± 1.56	0 ± 0	0 ± 0	0.42 ± 0.42	1.893	0.146
Prar	0.79 ± 0.54	0 ± 0	0 ± 0	0 ± 0	1.836	0.156
Acni	0.25 ± 0.25	0 ± 0	1.07 ± 0.72	0 ± 0	1.519	0.224
Grop	0.7 ± 0.7	0 ± 0	0.96 ± 0.96	0 ± 0	0.566	0.640
Poni	0 ± 0	0 ± 0	0.50 ± 0.50	0 ± 0	0.881	0.458
Zimo	1.81 ± 1.31	1.25 ± 1.25	1.95 ± 1.61	0.64 ± 0.64	0.278	0.840
Saol	0.1 ± 0.1	0 ± 0	0 ± 0	0 ± 0	0.881	0.458
Alle	0.28 ± 0.28	0 ± 0	0.35 ± 0.35	0 ± 0	0.559	0.644
Cade	0 ± 0	0 ± 0	1.23 ± 0.99	0 ± 0	1.344	0.273
Taap	0 ± 0	0 ± 0	1.22 ± 1.22	0 ± 0	0.881	0.458
Phda	0 ± 0	0 ± 0	0.25 ± 0.25	0.47 ± 0.47	0.482	0.696
Jure	0.52 ± 0.52	0.64 ± 0.64	0 ± 0	0 ± 0	0.942	0.429

Note: Different letter in the superscript means significant variations between the mean at $p < 0.05$, tested by post hoc Tukey HSD.

The second group was collectively dominated by *M. buxifolia* and *O. ferruginea*, including 06 sites and 411 individuals of 9 different species. The community was species-poor and less diversified among the resulted groups (Table 2). The sites of this group were located at high altitudinal ranges (mean= 1328.1 m) with comparatively steep slopes. The soil is generally characterized by low clay particles and high pH. Associated woody trees with importance value ≤ 2% in this community include *A. modesta*, *Z. mauritiana*, *M. alba* and *F. palmata*. The third group dominated by *M. buxifolia* and *E. globulus* was the second diversified group comprised of 946 individuals recorded in 12 sites. The sites sampled in this group were located at medium altitudes and moderate slope (Table 4). High nitrogen content (0.11% ± 0.03) is one of the most distinguished edaphic characters of this group. In addition, no evidence of past or recent human activities was recorded in these forests. The understory vegetation was characterized by abundant *D. viscosa*, *J. adhatoda*, *S. munja*, *V. negundo*, *C. arvensis* and *S. asper* etc.

Table 4. Habitat characteristics of *Monotheca buxifolia* dominated communities segregated by Wards Clustering.

	Mono-Acacia	Mono-Olea	Mono-Eugl	Mono	F	*P*
X_{Lat}	34.06 ± 0.40	33.89 ± 0.19	33.97 ± 0.27	31.18 ± 2.12	0.699	0.558
X_{Long}	71.50 ± 2.13 ^{a}	71.57 ± 0.24 ^{a}	71.65 ± 0.16 ^{a}	70.88 ± 0.22 ^{b}	3.758	0.0181
X_{Ele}	1038.03 ± 68.8 ^{a}	1328.1 ± 126.9 ^{ab}	1031.72 ± 90 ^{a}	1275.3 ± 80.68 ^{b}	2.887	0.0473
X_{Slope}	21.08 ± 2.85	28.5 ± 1.99	23.25 ± 2.92	26.79 ± 2.6	1.214	0.316
X_{Asp}	225.75 ± 29.85	203.3 ± 49.88	219.3 ± 24	254.93 ± 19.35	0.581	0.630
X_{Clay}	11.9 ± 1.09	11.67 ± 1.97	11.8 ± 1.12	13.9 ± 1.01	0.935	0.432
X_{Silt}	43.18 ± 3.41 ^{a}	41.62 ± 5.29 ^{a}	41.49 ± 4.01 ^{a}	29.63 ± 2.43 ^{b}	3.643	0.020
X_{Sand}	44.94 ± 3.77	46.65 ± 4.6	46.80 ± 4.6	56.58 ± 2.45	2.261	0.096
$X_{Texture}$	2 ± 0.21	2 ± 0.25	2.08 ± 0.22	2.36 ± 0.17	0.696	0.559
X_{pH}	7.78 ± 0.15 ^{a}	7.98 ± 0.21 ^{a}	7.97 ± 0.11 ^{b}	7.66 ± 0.18 ^{a}	0.892	0.053
$X_{\%\ OM}$	1.03 ± 0.37	1.82 ± 0.72	2.15 ± 0.66	1.53 ± 0.4	0.890	0.4541
$X_{\%\ Lime}$	2.16 ± 0.44	3.04 ± 0.85	2.87 ± 1.06	2.73 ± 0.29	0.280	0.8391
$X_{\%\ N}$	0.05 ± 0.02 ^{a}	0.10 ± 0.03 ^{a}	0.11 ± 0.03 ^{b}	0.07 ± 0.01 ^{c}	8.001	0.0002
$X_{P\ (mg/kg)}$	13.98 ± 1.42	16.8 ± 1.31	15.87 ± 1.34	14.38 ± 1.7	0.555	0.647
$X_{K\ (mg/kg)}$	144.25 ± 14.35	149.8 ± 25.76	146.17 ± 18.3	156 ± 15.6	0.103	0.9577
X_{FC}	0.25 ± 0.01	0.25 ± 0.01	0.24 ± 0.008	0.23 ± 0.006	1.187	0.3268
$X_{BD\ (g/cm3)}$	1.46 ± 0.02	1.46 ± 0.03	1.46 ± 0.01	1.49 ± 0.01	0.956	0.4227
$X_{AW\ (\%)}$	0.14 ± 0.01 ^{a}	0.14 ± 0.01 ^{a}	0.14 ± 0.01 ^{a}	0.12 ± 0.003 ^{b}	3.312	0.0295
$X_{Ec(\mu s/cm)}$	282.4 ± 25	332 ± 31.9	316.25 ± 25.2	325.07 ± 21.1	0.743	0.5326
X_{TDS}	155.33 ± 13.7	182.6 ± 17.54	173.96 ± 13.8	178.79 ± 11.63	0.7437	0.5323

Note: Different letter in the superscript means significant variations between the mean at $p < 0.05$, tested by post hoc Tukey HSD.

M. buxifolia exhibited unique distributions in 14 sites and were classified into single-species community (IVI = 97.49 ± 0.97). In the tree stratum, a total of 1019 individuals of the dominant and associated six species were recorded, but none of them occurred with ≥2% of importance values (Table 3). However, these co-dominant species were more widely distributed in other broadleaved forests in the region irrespective of changes in soil properties and other environmental variables. *M. buxifolia* pure community favor sandier soil textures and lower soil nutrient levels in comparison to other communities (Table 4). Topographic features revealed that these forest stands are located on an average elevation of 1275.3 m, with moderate (26.79° ± 2.6) slope inclination. The presence of clay in the lower soil layer explains high water availability. Generally, we observed scarce evidence of past human activities and terraces in less than 10% of the sampled sites.

In comparison to others, *M. buxifolia* individuals occurred in all sampled plots with different densities reflecting the broad distribution of the species in the studied area. Among the resulted communities, significance difference in the values of IVI for *M. buxifolia*, *O. ferruginea*, *A. modesta* and *A. altissima* was recorded using ANOVA and Tukey HSD test. Box Whisker plots were used to expose differences in the elevation, nitrogen, silt, pH and available water in the resulted groups (Figures 4 and 5).

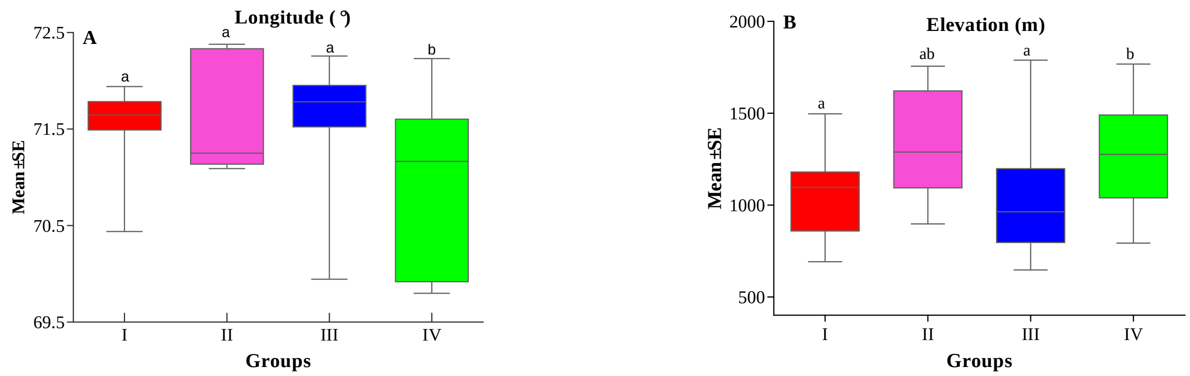

Figure 4. Box and Whiskers plot for topographic variables, i.e., (**A**) Longitudinal (°) and (**B**) Elevation variation among the *Monotheca* dominated groups. Colors represents four different vegetation types are given in Figure 2. Different letter in the superscript means significant variations between the mean at $p < 0.05$, tested by post hoc Tukey HSD.

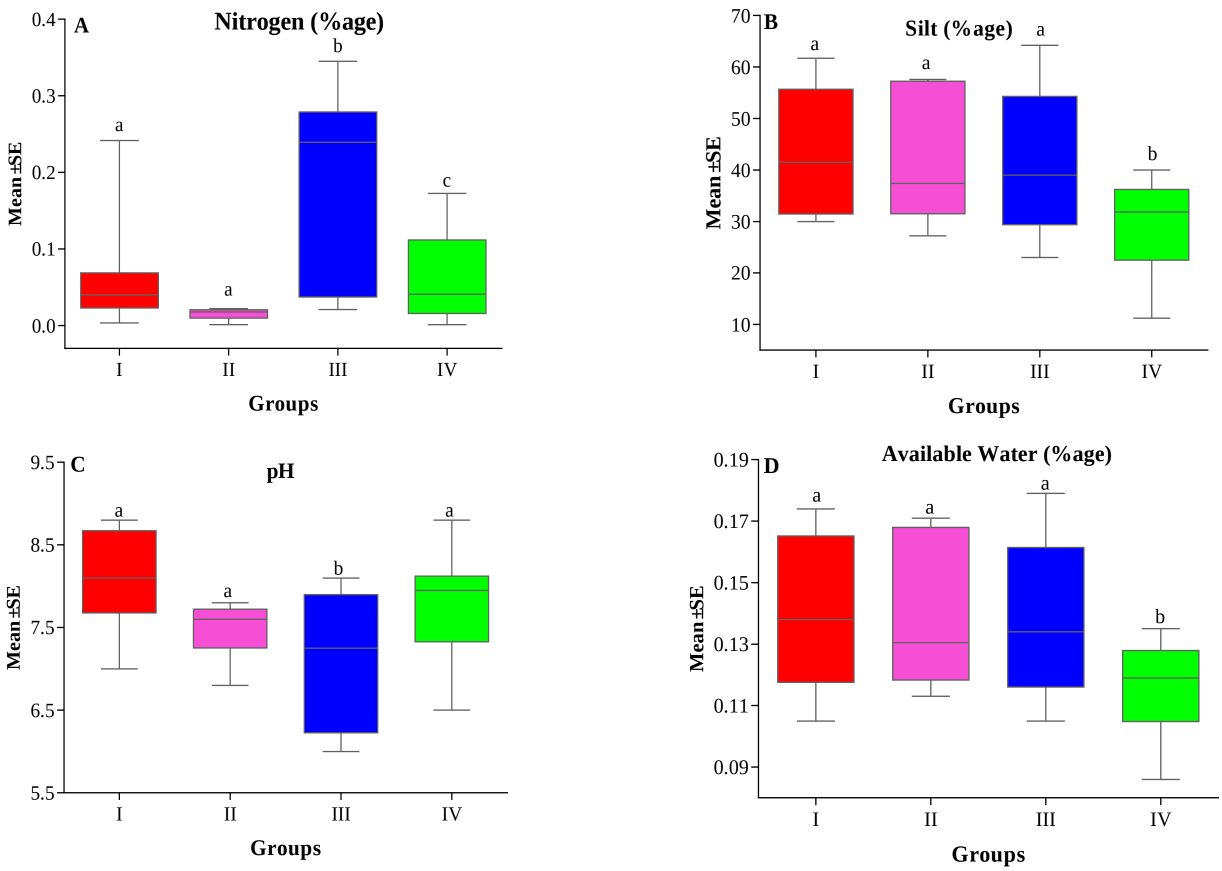

Figure 5. Box and Whiskers plots for soil physio-chemical properties, i.e., (**A**) Nitrogen (%), (**B**) Silt (%), (**C**) pH and (**D**) Available water (%) variation among the *Monotheca* dominated communities (Groups). Colors representing four different vegetation types are given in Figure 2. Different letter in the superscript means significant variations between the mean at $p < 0.05$, tested by post hoc Tukey HSD.

3.5. Stand Characteristics

Density (ha^{-1}) and basal area (m^2 ha^{-1}) of the dominant and associated tree species are offered in Table S4. Total tree density in Group-I was 323.67 plants ha^{-1} with *M. buxifolia* comprising 80% of the total. Among the other associated species, *A. modesta* shares 3.43% to the total. Tree density for Group-II ranges from 0.148 to 259.26, of which 84.7% was shared by the dominant species followed by *O. ferruginea* and *P. granatum*. Group-III possesses 296.2 individuals ha^{-1} of which 81.6% belongs to dominant individuals while the rest was shared by 16 associated tree species. Similar trend was observed in pure *Monotheca* group where the leading species shares 79.19% to the total density followed *Olea* and *Acacia*. Overall basal area for Group-III was 62.7 m^2/ha followed Group-I, Group-IV and Group = II, respectively (Table 5).

Table 5. Average number of trees (D/ha) and basal area (m^2/ha) of cut stumps, seedling, saplings, small, medium, large and mature trees for *M. buxifolia* communities obtained from Ward's agglomerative clustering techniques. Basal area for cut stumps, seedlings and saplings are not shown.

S.no	Categories	Community Types							
		Mono-Acacia		Mono-Olea		Mono-Eugl		Monotheca	
		D/ha	BA	D/ha	BA	D/ha	BA	D/ha	BA
1	Cut Stumps	33.33	×	22.22	×	30.37	×	20.95	×
2	Seedlings <3 cm	11.48	×	7.41	×	15.93	×	15.55	×
3	Saplings <5 cm	9.25	×	5.92	×	15.93	×	14.28	×
4	Small trees 5–30 cm	78.51	2.69	89.63	3.58	57.41	2.38	83.49	3.34
5	Medium trees 31–55 cm	114.81	17.01	140	17.39	128.15	14.66	136.51	16.51
6	Large trees56–80 cm	50.37	17.12	26.65	10.31	64.44	23.49	49.2	11.2
7	Mature trees < 80 cm	11.85	8.66	2.961	1.56	30	22.07	3.8	3.55
	Total	**309.6**	**45.48**	**294.79**	**32.84**	**342.23**	**62.7**	**46.25**	**34.62**

3.6. Regeneration Dynamics of Monotheca

A total of 2930 individuals of *Monotheca* were sampled over the 440 subplots. The recorded individuals were leaded by medium size class trees (DBH= 31–55 cm) with a percent share of 37.50 followed by small trees (26.21%) of DBH ranging from 5 to 30 cm. Table 5 shows highest number of cut stumps for *Monotheca-Acacia* community (33.33 individuals ha^{-1}) followed by *Monotheca-Eucal* community (30.37 stumps ha^{-1}), *Monotheca-Olea* community (22.22) and pure *Monotheca* forests (20.95 stumps ha^{-1}). The density of juveniles (i.e., seedlings and saplings) in Group-I was 11.48 and 9.25 plants ha^{-1}, respectively, comprising 7.50% of the total living population of *M. buxifolia.* Juveniles share 4.89%, 10.21% and 9.85% to the total population of Group-II, III and Group-IV, respectively (Table 5). The frequency distribution of DBH-classes showed high numbers of small and medium trees with fewer large trees and a heavy disruption in juvenile and mature stages (Figure S1). Medium trees with DBHs ranging from 31 to 56 cm contribute the maximum number followed by small trees (DBH 5–30 cm) and large trees (DBH 56–80 cm), whereas fewer were recorded for mature tress (DBH $\geq$ 80 cm) in *Monotheca-Acacia* community. Due to large diameter size, mature and large trees have high basal area (m^2 ha^{-1}) followed by small and young individuals. Similar pattern of density for DBH classes were found in Group-II and III. However basal area of Group-II was in contrast to Group-I and III with a peak for medium trees. Overall, trees were the highest shares (80.3%) in the population of the dominant species followed by cut stumps (10.09%), while juveniles (seedling + saplings) have 9.568% of the total. We investigated life tables, the survivorship, mortality rate and killing rate for the dominant species (Table 6). Group-II shows maximum mortality rate in sapling stage followed by Group-IV and Group-I. Similarly, mortality rate in medium trees ranges from 0.645 to 0.69 with a mean of 0.66 for all the reported groups, which is the second peak after sapling (Figure 6). The killing rate showed that fewer individuals were able to grow to small trees from sapling stage. Presence of high number of living individual of mature trees in Group-IV was due to low killing power.

Table 6. Life table for overall sampled, naturally growing forest stands of *Monotheca buxifolia* in Pakistan.

Dbh Classes	ax	Ix	dx	qx	Lx	tx	ex	kx
Seedlings	113	1000	230.0885	0.231	615.044	14,172.56	14.17	0
Saplings	87	769.911	−5495.58	−7.137	−2362.831	13,557.52	17.61	0.113559
5–30	708	6265.48	−3460.18	−0.552	1402.654	15,920.35	2.54	−0.91051
31–55	1099	9725.66	6530.97	0.671	8128.318	14,517.69	1.49	−0.19096
56–80	361	3194.69	1451.32	0.454	2323.001	6389.38	2	0.48349
<80	197	1743.36	1743.36	1	1743.362	4066.37	2.33	0.263041

Note: *ax* = survival individuals, *lx* = individuals surviving from the beginning to age x, *lx* = ax/a0 * 1000; *dx* = dead individuals from age x to x + 1, *qx* = (mortality from x to x + 1, *Lx* = average survival of individuals from age x to x + 1, *Tx* = total survival of individuals from age x, *ex* = life expectancy at age x, kx = killing rate.

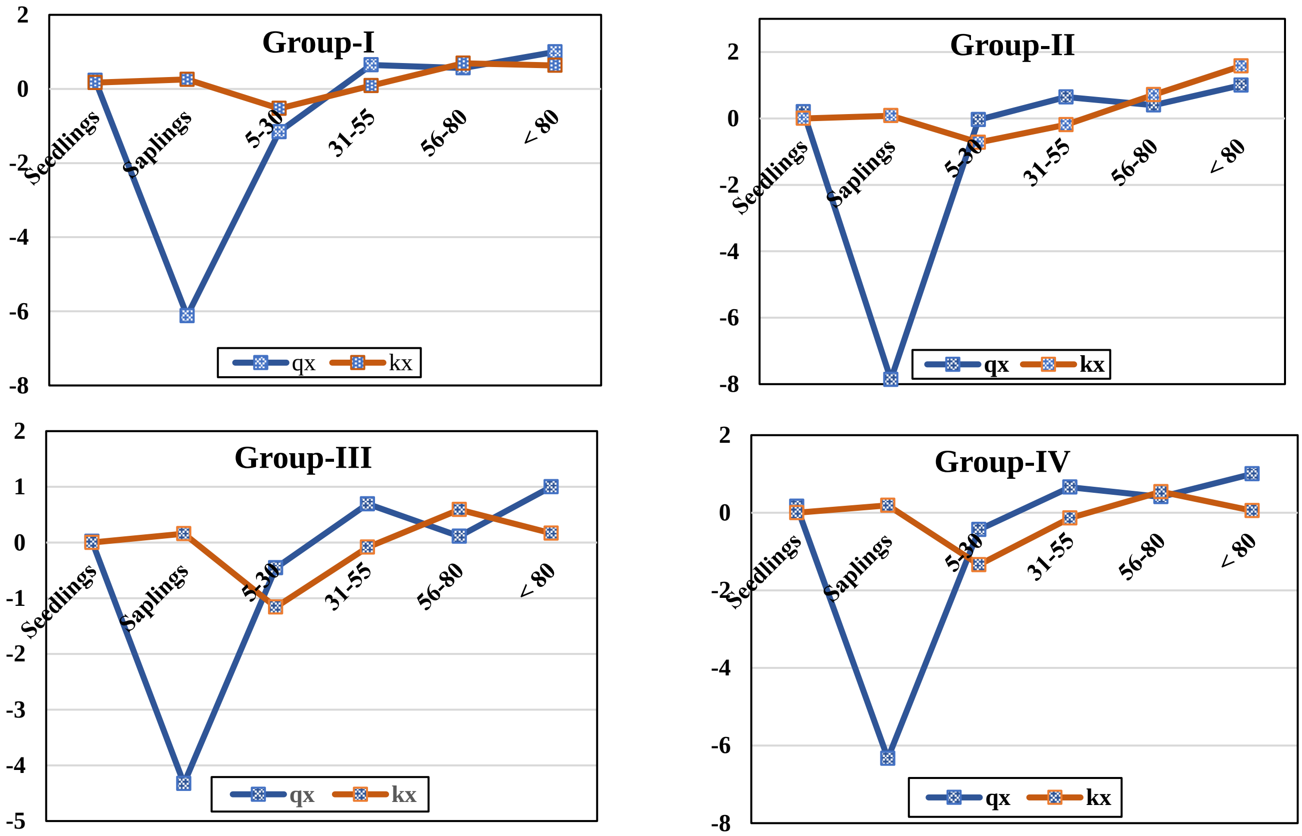

Figure 6. Mortality (qx) and killing power (kx) curves of seedling, saplings, small, medium, large and mature trees for *M. buxifolia* in Group-I to IV resulted from Ward's agglomerative cluster analysis of 44 stands.

4. Discussion

4.1. Floristic Composition and Chorology

Although forested areas of Pakistan (<5%) is much less than the desired 25%, still due to unique topography, soil types and climate, the area is presented by diverse flora of 6000 plant species [40]. The forested area is comprised of both conifers and broadleaved trees species with several endemic and exotic individuals. Floristic composition of the current study records 59 understories and 27 woody tree species (dbh ≥ 5 cm) of 22 families. The recorded woody flora shows 2 species of gymnosperms and 27 angiosperms that exhibits monocot nature with exception of *P. dactylifera*, exposing diversification of flora in natural microhabitats of the area [2]. Considering the fact that phytochory reflects climate condition, documented flora possess wide distribution ranges, representing several phytogeographical regions of the world, of which Irano-Turanian elements were the most prominent. Therefore, we come to the conclusion that the studied area is fit to Irano-Turanian region because of vicinity to Mediterranean and Euro-Siberian regions which is an agreement to the findings of Ali et al. [2]. Furthermore, the existences of endemic species are mainly due to climatic variability and climax in plant communities.

Plant life-forms are crucial to examine because they provide the fundamental structural components of vegetative stands and habitat condition. In the studied area, life-forms of the documented plants exhibited mega-phanerophytes to be the major component, which are the best representative of dense physiognomies [34]. We reported a high number of microphylls and mesophylls followed by leptophyllous and nanophyllous species. These findings are in agreement with Malik [51] and Qadir, [52] who documented high percentage of microphylls and nanophylls in Kotli Hill, Azad Kashmir.

4.2. RDA

We exposed the effect of topographic and edaphic variables on *Monotheca* phytocoenosis using RDA, a multivariate technique. RDA-ordination shows significance for a number of variables effecting the distribution of plant species in *M. buxifolia* dominated communities. Results of RDA show that elevation ($r = 0.481$), clay ($r = -0.527$), soil texture ($r = 0.447$) and lime ($r = 0.621$) were the most effective factors as earlier reported by Zhang et al. [53]. The importance of soil physiochemical attributes on vegetation dynamics and restoration has already been discussed by many authors [14,54,55]. Furthermore, organic matter, lime, and nitrogen have a key role in controlling photosynthesis, carbohydrate transport, protein synthesis, and other physiological activities; therefore, they are important in defining the vegetation types and species richness [56]. Natural vegetation is often used as a site indicator producing significant results due to its link with abiotic site characteristics such as nitrogen, which is one of the regulating soil factors for ecological groups in this study. Nitrogen is an essential nutrient for plants to perform different metabolic activities [57,58].

4.3. Classification of Monotheca Stands

Monotheca-Acacia (Group-I), *Monotheca-Olea* (Group-II), *Monotheca-Eucal* (Group-III) and *Monotheca* (Group-IV) were the four communities resulted from Ward's agglomerative cluster analysis using IVI of each woody tree species. *M. buxifolia* occurred in all the groups as a dominant element illustrating its wide range of distribution in the studied area [40]. *O. ferruginea* and *A. modesta* were among the other associated species reported as a strong companion to the dominant species, which supports the findings of Khan et al. [28]. Scant occurrence of some of the associates such as *Q. baloot*, *B. papyrifera*, *P. roxburghii, Z. armatum*, *P. gerardiana* and *P. nigra* reflects its narrow distribution with the dominant species. *M. buxifolia*, *F. palmata*, *M. alba*, *J. regia*, *P. armeniaca* and *P. granatum* were the common fruiting trees reported from the studied area [7]. *P. roxburghii* were planted recently in the running project of government "Billion Tree Tsunami Afforestation Project", which shows good signs for the future of these forests. Exotic plants (*A. altissima*, *B.* papyrifera, etc.) were also reported in weak association with the dominant species, whose adverse effects are highlighted by several workers [2,14,32,59]. These species should be discouraged properly in order to resist negative changes in originality and functions of native ecosystem.

Stands of Group-I and Group-III were positioned on low altitudes and lowest slope, while stands of Group-II were located at steep slope (28.5°) and high altitudes. Topographic variables such as elevation and slope significantly affect vegetation types due to their effect on specific microclimates [1,60]. In the present study, elevation ranged between 683 and 1728 m above sea level, and its significance in plant communities distribution and productivity rate in natural forests has been documented by several workers [61,62]. Similarly, slope also has visible effect on the distribution of plant species as steepness of the slope can reduce soil depths, nutrients, and moisture [63]. Stands present on steep slope were comparatively protected having no signs of current or previous human activities, which may be due to the inaccessibility for the locals [64]. *A. modesta* and *p. granatum* contain sites were faced to eastern and northwest aspect indicating the role of aspect in species distribution [32]. Similarly, edaphic factors are also very prominent, and they highly influence species composition, richness and diversity. The resulted four communities in the current study were facing different distinct soil physiochemical properties. Soil of Group-I was silty and found deficient in organic matter (%), lime (%), nitrogen (%) and electrical conductivity. The impact of the geological substratum's nature on soil characteristics and plant distribution has been well documented and studied in detail [10,12].

4.4. Stand Structure

Density and basal area are the most important components of forest resource management. In this study, stem density ranged from 296.04 (*Mono-Eucal*) to 324.7 (*Monotheca*) trees ha^{-1} with basal area ranging between 41.26 m^2 ha^{-1} (*Mono-Olea*) and 93.35 m^2 ha^{-1} (*Mono-Eucal*). Dominant species share 81.3% and 72.35% of total density and basal area (m^2 ha^{-1}) followed by *A. modesta* (5.25%, 8.84%) and *O. ferruginea* (3.47%, 7.05%), respectively. The density ha^{-1} for dominant and subordinate species is well in the range of other studies [16,27,28] but relatively higher from those reported by Nizami [65]. Tree basal area can be measured from diameter which can play a vital role in forest community distribution and effecting regeneration. Due to presence of larger diameter trees, *Monotheca* basal area was greater from those reported by Khan et al. [32]; however, the basal area of the associated species was in a similar range. In contrast, current basal area of the associated species was comparatively low in comparison to the findings of several workers (16,31,33,40]. The low basal area of associated species may possibly be due to a lower number of individuals and also due to the fact that *Monotheca* is a purely growing crop in many regions of the study area [28].

4.5. Size Classes and Regeneration

Timber execution depends on age class which refers to ratio of different age groups in a population at a given time [51]. Tree diameter rises with age; therefore, diameter of the trunk has been employed as an indicator of age with the fact that larger diameter trees will be older [66]. The presence of young plants from seedling to mature or over-mature stage shows chances of regeneration. *Monotheca* vegetation is very much affected by local activities, and their natural regeneration is prevented by heavy cutting, grazing and mining activities. Lower number of juvenile and mature trees with a peak in medium trees followed by small and large trees of the dominant species shows the disturbances in these forests. Lower number of seedlings and saplings may be due to over-grazing and logging of trees, which enhance the mortality rate of juveniles and affect the regeneration process [32]. Frequency of cut stumps highlights the interference of the local community, which supports the statement of several workers [63,65,66].

4.6. Implications for Conservation

Individuals as well as the government should take strong initiatives for protecting the structurally diverse M. buxifolia forests across its natural distribution range in Pakistan. Knowledge about these ecologically and commercially valuable forests needs to be extended so that people become aware of deforestation and its resultant consequences for wildlife, humans, and ecological systems. People's participation in the conservation and management of forests is of a great importance, so the public must become involved in this global task. Likewise, illegal cutting of forests should be banned, and afforestation programs like billion tree tsunami projects (ATTP) must be launched on a larger scale which might increase the population of these productive forests and would offer a great opportunity to deal with climate change impacts. Our current results on the structural dynamics of M. buxifolia forests might be useful in adopting conservation strategies for achieving multifunctional specific goals on biodiversity targets and sustainable forest landscapes in the long-term future perspective.

5. Conclusions

This study is the first comprehensive field research on *M. buxifolia* forests across the environmentally diverse landscapes in Pakistan. We proposed a first country-level classification of *M. buxifolia* forests based on floristic composition and environmental factors using numerical techniques. Based on this classification, the growth of *M. buxifolia* can be reasonably predictable on entire landscape of the country by observing plant-species distributions in the existing habitats conditions. We also believe that studies of the *Monotheca* at communities and individual species-level might provide a robust result and better understanding of vegetation–environment interactions than studying either one-alone. Most of the forest stands distributed in four distinct woody species communities are old and moderately dense with naturally poor *M. buxifolia* recruitment due to several underlying factors such soil physiochemical properties, anthropogenic intervention, climatic induced factors and understory species coexistence, etc. These overriding factors are responsible for community composition and recruitment dynamics emphasizing the fact that the conservation of *M. buxifolia* and co-occurring species in the future is compromised. Therefore, management plans are indispensable in order to assure either the artificial or natural regeneration of *Monotheca* in relation to the main objectives attributed to these formations (e.g., fruit production, wood supply, fodder for grazing) and future threats to these ecosystems. Likewise, we recommend further detailed studies at both local and regional scales to disentangle the vegetation–environment relationships, considering other spatial biotic and abiotic gradients for better understanding of these less disturbed microhabitats at environmentally diverse landscapes. We further recommend that local inhabitants must be educated through campaigns which would develop positive attitudes toward forest protection and development.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14106111/s1, Table S1: A brief detail of the documented woody tree species.; Table S2: Summary of families, tree type, life-form, leaf-spectra and chorologies of the documented tree species; Table S3: Correlation and biplot score of RDA showing the result of sites-environment of 44 Monotheca vegetation sites; Table S4: Structural attributes of 27 tree species distributed in four communities. Means values were computed following Analysis of Variance for comparison; Figure S1: Diameter class distribution of seedling (>3 cm), sapling (3–5 cm), small trees (5–30), medium trees (30–55 cm), large trees (55–80 cm) and mature trees (>80 cm) of Monotheca in Pakistan; Figure S2: Representatives from (A) *Mono-Olea*, (B) *Mono-Acacia*, (C) *Mono-Olea-Acacia* mixed forest, and (D) scares vegetation of *Monotheca*.

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