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Phosphorus Dynamics in *Nannorrhops ritchieana* (Mazri) Forests Across Different Climatic Zones of Pakistan: A Framework for Sustainability and Management

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Simple Summary

Mazri palm forests in Pakistan and neighboring countries are vital for the ecosystem and local communities that depend on them. However, little is known about how soil nutrients, such as phosphorus, control the growth and health of these forests. In this study, we examined Mazri forests in Pakistan's Khyber Pakhtunkhwa region, gathering soil and plant data from over 500 locations across different climate zones. We measured soil phosphorus levels and studied the abundance and traits of Mazri palms to identify links. Our findings indicate that phosphorus alone does not strongly control the distribution of Mazri forests, although slight differences appear in some regions. The forests remained relatively stable in wetter and drier mountain areas, while there were slight changes in abundance in other zones. These findings show that soil nutrients and climatic factors affect the distribution of Mazri palms. Understanding these patterns can help guide conservation efforts and promote the sustainable use of Mazri forests, which are essential for local livelihoods and ecosystems.

Abstract

Nannorrhops ritchieana (Mazri) forests are found in Pakistan, Afghanistan, Iran, and Oman. These forests are ecologically and economically important to local communities and exhibit complex spatial distributions. This research examines the distribution of Mazri forests and their responses to varying phosphorus levels across different climatic zones. We collected data from 508 plots in the Khyber Pakhtunkhwa region of Pakistan, gathering 500 g of soil from each plot for phosphorus analysis, along with measurements of abundance and various traits. A distribution map was constructed to assess the impact of phosphorus levels on Mazri forest distribution and traits across climatic zones. Using a PCA biplot, we visualized the abundance and density and studied the effects of different climatic and

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environmental factors. Our findings suggest that phosphorus levels do not significantly influence the distribution of Mazri forests, which vary across different climatic regions. Forests are stable in the eastern wet mountain zone (EWMZ) and northern dry mountain zone (NDMZ), although without a significant pattern. A weak positive correlation was observed in the western dry mountain zone (WDMZ). In contrast, the Sulaiman piedmont zone (SPMZ) presented minor variations in abundance, indicating that phosphorus, in conjunction with other edaphic and climatic factors, affects Mazri forest distribution and abundance. Further research is needed to investigate the combined effects of various soil nutrients and climatic factors on the distribution, abundance, and functional traits of Mazri forests across different regions.

Keywords: palm abundance; climatic zones; functional traits; Mazri forests; *Nannorrhops ritchieana*; phosphorus

1. Introduction

Understanding how the distribution, density and abundance of a species vary along environmental gradients is a primary goal of ecology [1]. Determining a species' response to environmental factors is crucial for understanding why some species are rare and others are abundant in an ecosystem [2,3]. These responses involve complex linkages between soil nutrients and plant traits, underscoring the role of plant functional diversity in various ecological processes [4–6]. Nutrients are essential for soil fertility and have also been demonstrated to influence plant species composition and function [7]. Phosphorus, in many ways, is an essential ecological gradient that controls plant occurrence, abundance and health [8,9].

Phosphorus is critical in biosynthesis, photosynthesis, respiration, and enzyme regulation [10]. As one of the 17 most essential nutrients, it controls plant growth, signaling, membrane stability, energy production and nitrogen fixation [11]. Its concentration in plants typically ranges from 0.05–0.50%, revealing its importance in different physiological processes [12]. Plants absorb phosphorus from the soil as orthophosphate [13], but its bioavailability is controlled chiefly in arid and semiarid climatic regions because of its strong bonding with soil minerals [14,15]. These restrictions highlight the need to disentangle phosphorus dynamics to ensure sustainable ecosystem productivity and resilience under changing climatic conditions [16–18]. The impact of phosphorus on the abundance of various plant species has been studied across different ecosystems [10,19–21]. However, its influence on palm species distributed across diverse climate zones is less understood. To address this gap, we selected the palm *Nannorrhops ritchieana* (Griff.) Aitch as a model species due to its wide distribution, making it excellent for investigating plant–phosphorus interactions.

Nannorrhops ritchieana is a native palm species of Pakistan, Afghanistan, Iran, Oman, Saudi Arabia and Yemen [22]. It is a gregarious palm with strong adaptation potential. It can survive harsh environmental conditions, including strong winds, extreme temperatures (0 to 52 degrees Celsius), and scarce water. It prefers magnesium-rich soil to grow.

This palm species grows in the wild and is cultivated along field banks and in home gardens for its economic and aesthetic value [23]. For traditional communities, particularly in the tribal regions of Pakistan, Mazri is a crucial source of income [22]. People weave various products, such as handicrafts and utensils, from their leaves. These items are sold in local markets, providing essential financial support for families. The palm fibers produce approximately 40 different types of goods [24]. In addition to humans, various birds make nests in their trunks. The Indian porcupine eats its roots and, therefore, raises significant conservation concerns [25].

In arid regions, where precipitation and soil available phosphorus are scarce, Mazri forests adapt to harsh conditions through nutrient-use mechanisms [21]. On the other hand, in subtropical and humid regions where monsoon rainfall is frequent, nutrient cycling occurs more quickly, increasing phosphorus availability and directly influencing species abundance and ecological interactions [26].

Mazri forests are distributed across Pakistan, from the Arabian coast to the Himalayan Mountains, and span a wide range of environmental conditions [22]. In the southwest, they occur in areas with low precipitation and nutrient-poor soils, whereas in the north, they grow in regions with high rainfall and nutrient-rich soils [25]. This broad environmental range makes N. ritchieana a model palm species for studying phosphorus dynamics and their implications for conservation and sustainability.

Shifts in nutrient availability can lead to critical changes in the structure and function of an ecosystem [27]. These shifts highlight the importance of understanding phosphorus cycling within the context of global nutrient dynamics and plant adaptation mechanisms. Insights from global studies suggest that P dynamics are not only crucial to forest health but also essential to broader nutrient cycling processes, which are critical to climate change [16].

The palm occurs in the wild and is cultivated on field banks for its economic benefits [21,22,25]. In Pakistan, Mazri forests are sporadically distributed in regions with low precipitation and poor soil nutrient contents in the southwestern parts, with maximum rainfall and rich soil nutrient contents in the northern parts [21]. These environmental conditions make it a model palm species for understanding phosphorus dynamics from a resource conservation and sustainability perspective. Phosphorus in such climatic regions is often tightly bound to parent rocks, limiting its bioavailability and absorption [15]. Studies conducted across different regions of the globe, where phosphorus dynamics have been disentangled, reveal how crucial and critical phosphorus cycling is to plant health and productivity [16]. This study highlights phosphorus dynamics and their importance for Mazri forest management across various climatic zones.

By examining soil phosphorus availability and plant density across 508 plots in four climate zones, this study tests the following hypotheses: (H1) Phosphorus availability significantly influences the distribution and abundance of Mazri forests across various ecosystems. (H2) Implementing specific management practices to increase soil phosphorus availability directly supports the conservation and sustainability of Mazri forests. This research aims to assess the role of soil phosphorus in shaping the distribution, abundance, and stability of Mazri forests. The objectives of this study are to (1) measure phosphorus levels and Mazri palm abundance in different climatic zones; (2) analyze the relationship between phosphorus availability and forest distribution; and (3) develop a framework for sustainable management strategies that prioritize both soil fertility and conservation goals.

2. Materials and Methods

2.1. Study Area

The province of Khyber Pakhtunkhwa is characterized by its topographical diversity and is situated in the northwest region of Pakistan at 31°49′–35°50′ N latitude and 70°55′–71°47′ E longitude. It covers an area of 101,741 square kilometers. The province shares a lengthy border with Afghanistan to the northwest, whereas Punjab lies to the southeast. Additionally, it is bordered by Azad Kashmir to the east and Baluchistan to the southwest (Figure 1). The province is home to three significant mountain ranges: the Hindukush, the Himalayas, and the Karakoram. These ranges are in eastern Khyber Pakhtunkhwa, specifically within the Eastern Wet Mountain Zone (EWMZ), which includes the Hazara Division. The Northern Dry Mountain Zone (NDMZ) to the north encompasses the Malakand Division. In contrast, the western region is designated the

Western Dry Mountain Zone (WDMZ), which includes portions of the Kohat and Peshawar Divisions. The southern parts of the province are characterized by central plains and valleys in Sulaiman Mountain and are referred to as the Sulaiman piedmont zone (SPMZ). The district in the northern part of the province has the highest altitude, experiences the lowest temperature in winter and hosts many glaciers. On the other hand, Dera Ismail Khan, located in the southern part of the province, experiences the lowest temperatures in winter, offering an optimal climatic opportunity for agriculture.

Figure 1. Topographical map of Khyber Pakhtunkhwa, which displays various climatic zones depicted by different colors. The black dots represent Mazri forest sampling across all zones.

2.2. Soil Features

The soil types vary greatly across the bioclimatic zones. The EWMZ generally has deep, well-drained loams with moderate organic matter, supporting relatively dense vegetation. Shallow, gravelly, and sandy loams with low water retention rates mainly dominate the NDMZ. The WDMZ features sandy loams and sandy clay loams, which are often calcareous and low in nutrients. In the SPMZ, the soils are mostly alluvial and colluvial, ranging from silty loams to clay loams, with fertility depending on sediment deposition. Overall, phosphorus availability is usually low to moderate and is affected by erosion, land use, and local geology.

2.3. Geobotanical Description

Vegetation patterns reflect the interactions among climate, soil, and topography. In the EWMZ, Mazri palms grow alongside broadleaf species such as *Quercus baloot* and *Olea ferruginea*. The NDMZ and WDMZ host more open stands of Mazri palms mixed with xerophytes such as *Ziziphus nummularia*, *Capparis spinosa*, and *Acacia modesta*. The SPMZ features xerophytic vegetation dominated by *Capparis decidua*, *Acacia modesta*, *Prosopis juliflora*, *Phoenix dactylifera*, *Periploca aphylla*, and *Calotropis procera*. The southern areas are known primarily for the large-scale production of *Phoenix dactylifera* fruits distributed throughout Pakistan.

2.4. Data Collection

We studied 63 *Nannorrhops ritchieana* (Mazri palm) populations across 508 plots, each measuring 10 × 10 m. Sixteen of these plots were in the EWMZ, 162 in the NDMZ, 222 in the WDMZ, and 107 in the SPMZ. In each plot, we recorded vegetation parameters, including density (number of *N. ritchieana* individuals per plot) and abundance (the total number of individuals recorded across all plots at a given site). The cover was visually estimated via the Braun-Blanquet scale and converted to % cover. Palm height was measured via a measuring tape from ground level at the base to the tip. The leaf number indicates the total number of fully developed leaves per palm, whereas the number of segments per leaf refers to the number of leaflets in a mature, fully expanded compound leaf; three randomly selected leaves per individual palm were counted. Leaf length and width were measured in centimeters from the base to the tip (length) and across the leaf's broadest part (width). For soil analysis, 500 g of soil were collected from the rhizosphere at a depth of 0–35 cm after surface debris was removed, stored in labeled zip-lock bags, shade-dried at room temperature for one week to prevent fungal growth, and then sent to the Ecology and Conservation Laboratory for physicochemical analysis.

2.5. Soil Available Phosphorus Determination

The soil available phosphorus was measured via the Olsen method [13]. A 0.5 M sodium bicarbonate ($NaHCO_3$) solution with a pH of 8.5 was prepared. Ten grams of soil was added to a 250 mL flask, followed by 50 mL of $NaHCO_3$ solution. The mixture was shaken adequately on a shaker at 200 rpm for 30 min. Then, the solution was filtered through Whatman filter paper, and the filtered extracts were reacted with molybdate-ascorbic acid solution to produce a blue color proportional to the phosphorus concentration. The blue color intensity was measured with a spectrophotometer at a wavelength of 882 nm. A calibration curve was generated using standard solutions with known phosphorus concentrations for quantification. During analysis, blank and duplicate solutions were included to ensure the accuracy of the results. We also processed reagent blanks (without soil) alongside the samples to account for any phosphorus contamination. Each soil sample's available phosphorus (mg/kg) concentration was measured following the Olsen method protocol [13].

2.6. Data Analysis

We mapped the distribution of Mazri under the influence of phosphorus concentration along different climatic zones via ArcGIS 10.3. The distribution pattern of phosphorus was observed through density and box plots in R Statistical Software (v4.1.2; R Core Team 2021) via the 'ggplot2' package [28]. We used scatter regression for all four zones together via the ggplot2 package. We used a principal component analysis (PCA) biplot to understand the impact of various environmental variables on plant abundance and traits across the studied region via the factoextra package [29] in R Statistical Software.

3. Results

3.1. Impact of Phosphorus Pools on Mazri Attributes

In all the zones studied, *N. ritchieana* was the leading species associated with xerophytic shrubs and herbs (e.g., *Acacia modesta*, *Capparis decidua*, *Prosopis juliflora*, *Ziziphus nummularia* and *Aerva javanica*). However, as described previously, the phosphorus concentration was significantly correlated with only N. ritchieana traits (height, density, and leaf phosphorus content). In the Eastern Wet Mountain Zone (EWMZ), Mazri was distributed across an altitudinal range of 523–1217. The phosphorus level in the soil was moderate, ranging from 4.34 to 32.48 mg/kg. The palm population density was sparse, varying from 1 to 12 individuals, with 4–72% cover. The palms reach 74.5–178 cm in height, bearing 3–15 leaves per individual, with an average leaf length of 66.04 cm and a width of 72.39 cm. In the Northern Dry Mountain Zone (NDMZ), the palms are distributed at 547–1541 m, with phosphorus levels ranging from 3.12 to 71.40 mg/kg. The population density varied from 1 to 18 individuals; the cover was 2–95% (Figure 2). Palm heights range between 45.5 and 173.9 cm, with 2–19 leaves per individual. The mean leaf length was 54.64 cm, and the width was 41.66 cm (Table 1). Moreover, in the Western Dry Mountain Zone (WDMZ), the palms are distributed at an altitude of 437–2163 m. The soil phosphorus content is highly variable, ranging from 1.11 to 117.59 mg/kg. The palm density was moderate, with 1–24 individuals, and the cover ranged from 6 to 98%. The palms were between 38.09 and 269.11 cm tall and had 2–15 leaves, with mean leaf dimensions of 69.49 cm in length and 54.96 cm in width. Moreover, in the Sulaiman Pied Mount Zone, Mazri is distributed at 245–1340 m elevations, with soil phosphorus levels ranging from 2.33 to 52.84 mg/kg (Figure 2). The population density was sparse to moderate (1–17 individuals), with 5–88% cover. The palms are between 53.82 and 240.13 cm in height and bear 3–25 leaves, with an average leaf length of 61.33 cm and width of 50.71 cm (Table 1).

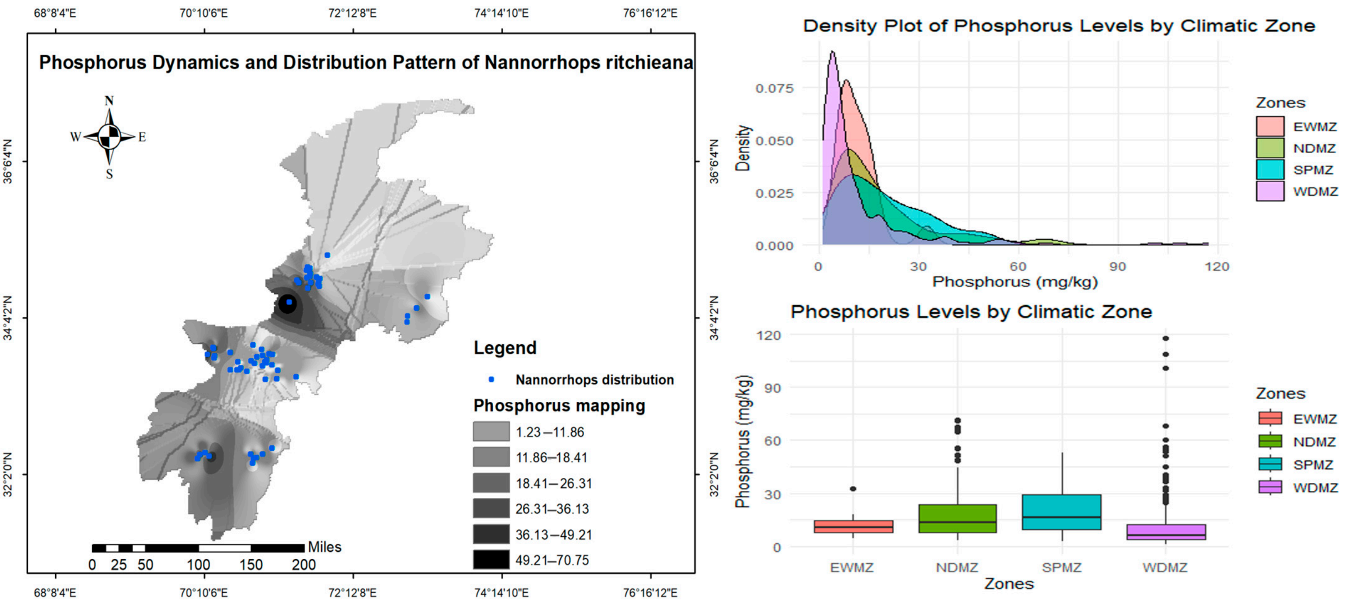

Figure 2. The map illustrates Mazri geographic location within the study area, with sample points marked by blue dots. The background shading represents varying levels of phosphorus in the soil, ranging from low to high values. The density and box plot of phosphorus levels by climatic zone show the distributions of phosphorus levels in the different climatic zones.

Table 1. Descriptive statistics of phosphorus plant abundance and traits.

		Phosphorus mg/kg	Density Individuals (10 × 10 m^2)	Cover (% Area Covered)	Abundance (Individuals/ Site)	Palm Height (cm)	Leaf Number	Segments Number	Leaf Length (cm)	Leaf Width (cm)
EWMZ	Min	4.34	1.00	4.00	27.00	74.52	3.00	8.00	45.72	33.02
	Max	32.48	12.00	72.00	100.00	178.03	15.00	29.00	109.22	129.54
	Mean	11.97	4.00	29.40	61.37	112.03	6.60	18.85	68.73	77.17
	Std. error	1.37	0.79	4.04	5.19	6.45	0.72	1.25	3.96	6.50
	Variance	37.76	12.42	327.20	538.96	833.23	10.25	31.29	313.61	845.47
	Stand. dev	6.15	3.52	18.09	23.22	28.87	3.20	5.59	17.71	29.08
	Median	11.13	2.00	26.00	59.33	107.65	6.00	20.50	66.04	72.39
NDMZ	Min	3.12	1.00	2.00	22.22	45.54	2.00	7.00	27.94	7.62
	Max	71.40	18.00	95.00	100.00	173.89	19.00	24.00	106.68	88.90
	Mean	18.36	3.20	42.44	74.08	89.06	6.54	14.04	54.64	41.66
	Std. error	1.17	0.24	1.88	1.91	1.75	0.21	0.27	1.07	1.15
	Variance	219.95	9.14	573.33	590.35	496.41	6.86	11.92	186.84	213.33
	Stand. dev	14.83	3.02	23.94	24.30	22.28	2.62	3.45	13.67	14.61
	Median	13.54	2.00	40.00	71.83	86.94	6.00	14.00	53.34	40.64
WDMZ	Min	1.11	1.00	6.00	25.00	38.09	2.00	7.00	23.37	15.24
	Max	117.59	24.00	98.00	100.00	269.11	15.00	39.00	165.10	137.16
	Mean	11.59	5.41	46.96	78.05	113.26	5.62	16.19	69.49	54.96
	Std. error	1.09	0.23	1.44	1.09	2.82	0.12	0.38	1.73	1.68
	Variance	262.09	11.57	458.56	262.29	1770.02	3.10	32.44	666.20	623.14
	Stand. dev	16.19	3.40	21.41	16.20	42.07	1.76	5.70	25.81	24.96
	Median	5.99	4.00	47.00	77.84	111.79	6.00	16.00	68.58	53.34
SPMZ	Min	2.33	1.00	5.00	33.33	53.82	3.00	0.00	33.02	12.70
	Max	52.84	17.00	88.00	100.00	240.13	25.00	30.00	147.32	111.76
	Mean	19.64	4.45	43.36	80.28	99.96	7.33	17.68	61.33	50.71
	Std. error	1.27	0.35	2.16	1.73	2.52	0.29	0.56	1.55	1.38
	Variance	171.69	13.22	495.39	316.37	673.47	8.79	33.31	253.48	202.54
	Stand. dev	13.10	3.64	22.26	17.79	25.95	2.97	5.77	15.92	14.23
	Median	16.14	3.00	38.00	78.99	96.88	7.00	18.00	59.44	52.45

3.2. Response of Plant Traits to Phosphorus Concentrations

We observed a weak negative trend in density across the EWMZ, with a slight influence of phosphorus. In contrast, in the NDMZ, the density was consistent across low phosphorus levels, but a minimal decrease was observed at relatively high phosphorus levels (Figure 3). The WDMZ shows slight variability with a positive influence at a moderate phosphorus level, whereas the SPMZ displays scattered values with no clear pattern. Conversely, the cover shows a weak pattern across all zones. The EWMZ and NDMZ exhibit minimal decreases with increasing phosphorus, whereas the SPMZ and WDMZ show scattered trends without correlation. The abundance, such as density, is relatively stable in the EWMZ and NDMZ but has no significant pattern. However, in WDMZ, a weak positive impact was observed, revealing that higher phosphorus may influence plant abundance in this zone. The SPMZ shows minute variations in cover. Palm height displays a weak positive pattern in the WDMZ, suggesting that phosphorus might affect plant growth. In other zones, height is mostly not affected by phosphorus levels. In all zones, the leaf number did not significantly differ with respect to phosphorus content. The scattered data points in the EWMZ and SPMZ indicate high variation, whereas those in the NDMZ and WDMZ show similar responses. Leaf length has a weak positive correlation in WDMZ, suggesting that phosphorus may have a minimal influence. In the remaining zone, no significant pattern was observed. The leaf width in the EWMZ and NDMZ has a weak negative pattern, indicating that phosphorus has a weak influence. In the WDMZ, a weak positive trend was observed, whereas the SPMZ showed no significant relationship. The number of segments per leaf exhibited minimal variation across zones, with no clear trends across phosphorus levels (Figure 3).

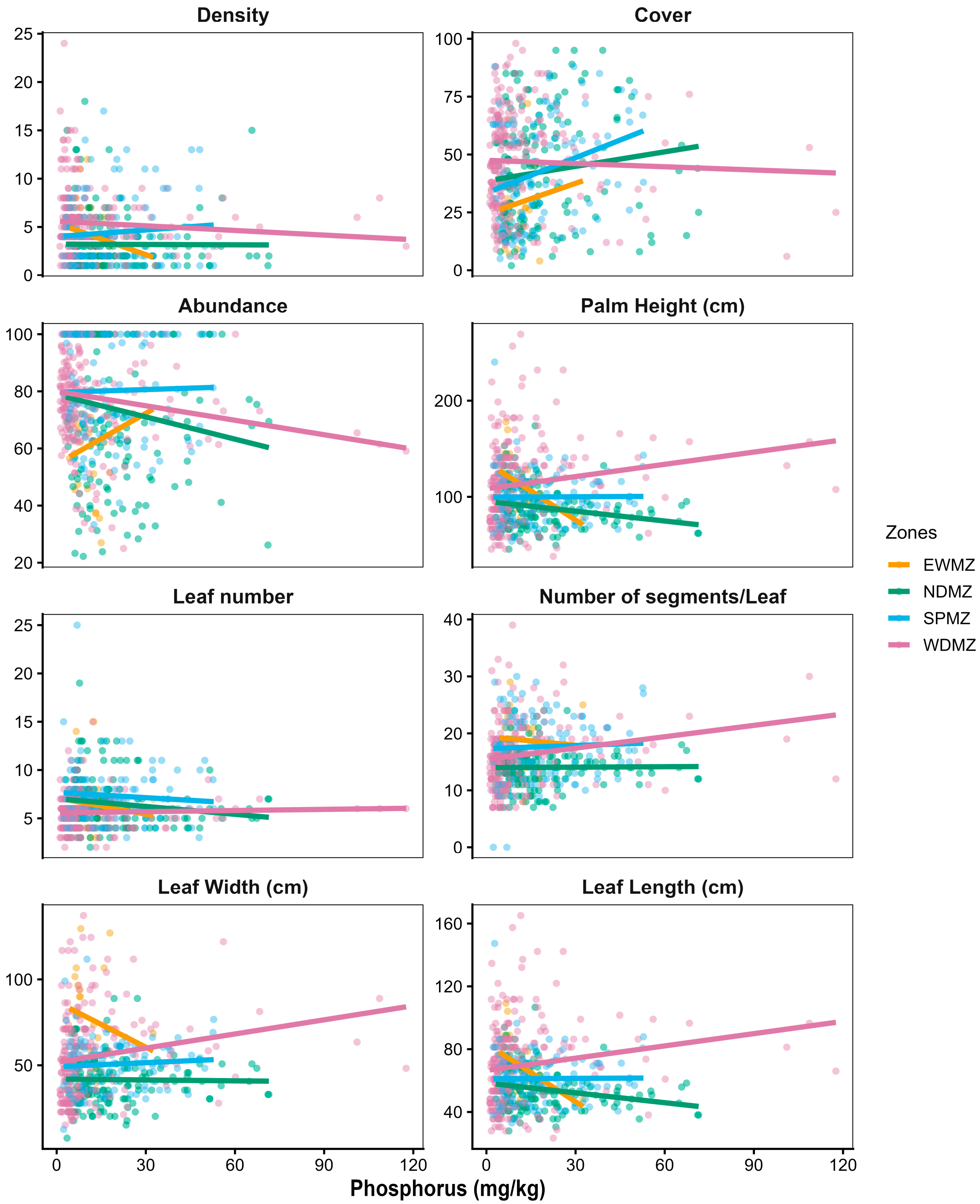

Figure 3. Illustration of Mazri forest abundance and other traits under the influence of phosphorus across different climatic zones.

3.3. Multivariate Analysis

We used a PCA biplot to display the spatial distributions and relationships among different traits and ecological factors across the four ecological zones. PC1 and PC2 collectively explained 43.2% of the variance in the dataset, with PC1 contributing 27.7% and PC2 contributing 15.5% (Figure 4). PC1 is strongly influenced by temperature, precipitation, and leaf length and width, whereas PC2 is linked with phosphorus content and plant density, suggesting local variations in habitat features. Variables such as latitude, humidity, and leaf length strongly correlate with PC1. Moreover, plant density and phosphorus contributed more to PC2, with longer arrows indicating a more substantial influence on the principal components. The ecological zones are demarcated, showing the influence of geographical and environmental factors on Mazri distribution and traits. Environmental factors coupled with plant traits provide a simplified yet comprehensive representation of the multivariate dataset, revealing the dominant axes of ecological and morphological variation.

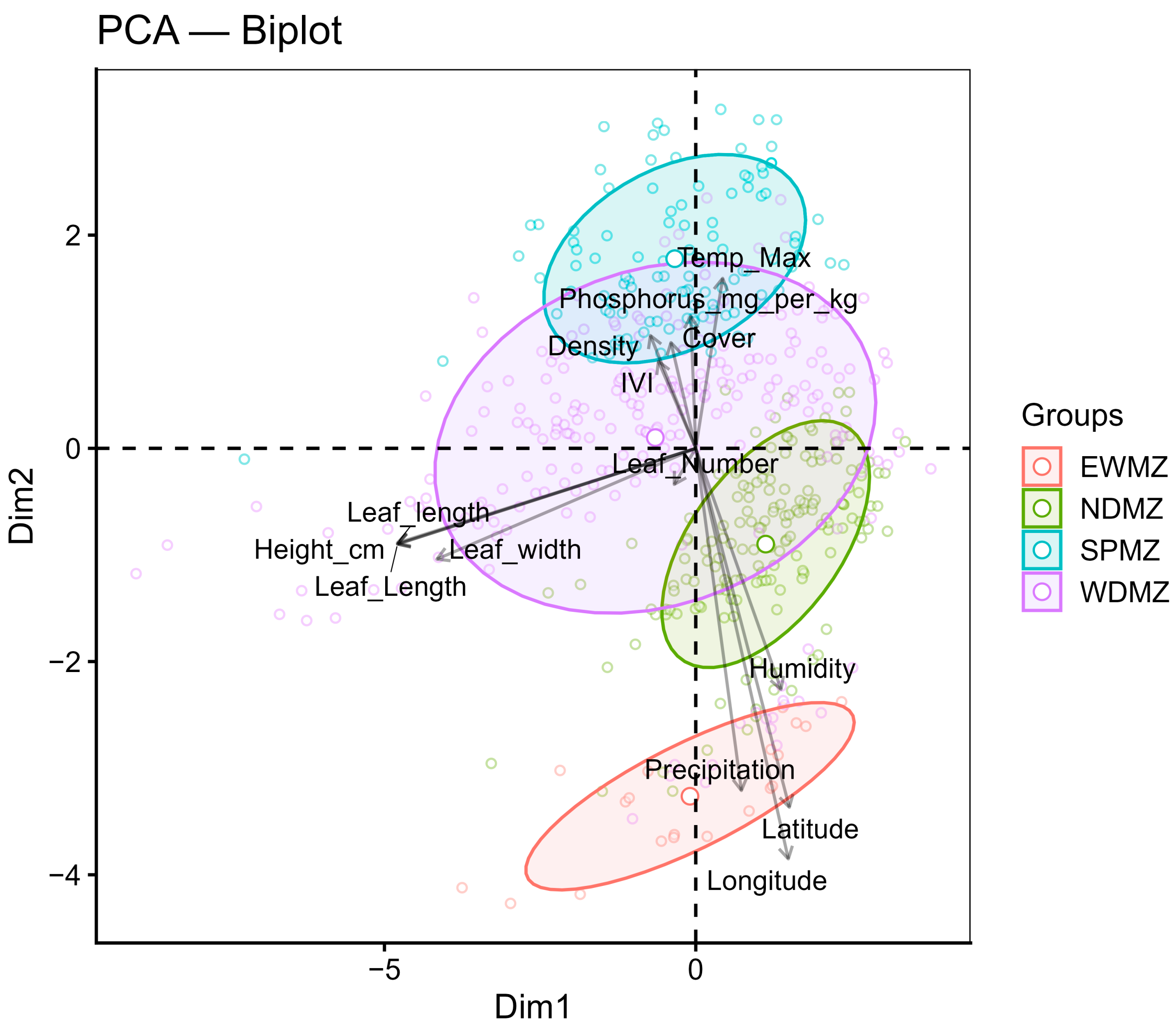

Figure 4. The PCA biplot displays the clustering of various Mazri traits under the influence of phosphorus and various climatic and topographic factors.

4. Discussion

In arid and semiarid climatic regions, phosphorus availability is well known and crucial for plant growth [30,31]. Our results are similar to those of studies documenting spatial variability in phosphorus levels driven by climatic and edaphic factors [32]. Compared with those in the EWZM and WDMZ, the phosphorus levels in the NDMZ, WDMZ and SPMZ were greater (Table 1), suggesting that moderate precipitation and temperature factors provide suitable conditions for phosphorus cycling. These findings contrast the results in arid regions, where phosphorus is mostly uniformly limited [33]. We recorded Mazri from several graveyards in the NDMZ and WDMZ, where decomposing bodies contribute significantly to the phosphorus in the soil. Our spectrophotometric analysis revealed peak curves in the graveyard samples, which were primarily represented as outliers, as shown in Figure 2. The SPMZ soil was notably fertile, with large canopy palms exhibiting the maximum phosphorus content. The link between biodiversity and human burial is supported by [33,34], but further research is needed to clarify this relationship. In western Amazonia, canopy palms present relatively high mean soil phosphorus values [1], consistent with our findings. American palms are associated with aluminum, clay, and nutrient concentrations [1,35], whereas Mazri palms are strongly related to magnesium, calcium, and iron across Pakistan. Additionally, palms in the western Amazon demonstrate similar soil preferences across regions [36]. Our results contrast, as Mazri palms are found in poor and rich soils, indicating a response on the basis of trait size.

4.1. Environmental Factors and Mazri Palm Morphological Adaptations

Our PCA results suggest that temperature and precipitation are the variables that substantially contribute to PC1, whereas PC2 displayed variation related to density and phosphorus (Figure 4). Similarly, previous studies have shown that these factors are key drivers in nutrient-limited ecosystems [37,38]. In addition, leaf traits were also significant contributors, highlighting the importance of functional adaptations in resource acquisition. However, our findings are similar to those of [39], who suggested that temperature significantly influences leaf morphology in arid ecosystems. This connection could be linked to similarities in the climatic zones.

4.2. Spatial Patterns of Distribution

The observed grouping patterns in scatter and PCA biplots confirm the ecological importance of climatic factors in shaping the distribution pattern of Mazri. However, our results highlight considerable variations, especially the broader spatial overlap of the NDZM and SPMZ, revealing shared ecological characteristics. Notably, the grouping observed in the SPMZ aligns with the hypothesis that moderate climatic conditions promote biodiversity and productivity [40]. Moreover, the limited distribution in EWZM suggests that the species has recently migrated to this zone. We observed that Mazri individuals in this zone are very young, and the local people are mostly unaware of their use for different purposes, as is the case in other parts of the study area. The WDMZ raises concerns about the vulnerability of these zones to climatic changes. The roles of high temperatures and scarce precipitation require further exploration.

4.3. Implications for Ecosystem Functioning

Phosphorus is essential for ecosystem function and productivity, yet its dynamics remain poorly understood in arid and semiarid regions [6,18]. The observed impact of phosphorus levels on functional traits provides crucial insights into the functional ecology of Mazri forests. This species exhibits physiological and morphological adaptation mechanisms that enable it to thrive under varying nutrient availability, similar to other desert species [41]. This study was designed to evaluate phosphorus dynamics specifically in *N. ritchieana* forests. The analysis of associated vegetation was limited to qualitative observations. Our results reveal the species' responses to phosphorus availability rather than community-level shifts. Nevertheless, associations (e.g., Acacia modesta and Capparis decidua) at higher-P sites may suggest that phosphorus availability also subtly affects cooccurring species, a question that warrants further research. Our findings suggest additional research on adaptation mechanisms in Mazri, focusing on morphological, functional, anatomical, and biochemical traits in response to different climatic and edaphic factors. Integrating these findings with ongoing forest plantation and conservation programs in Khyber Pakhtunkhwa could help select the right plants for the right place.

4.4. Synthesis and Future Perspectives

This research provides a comprehensive understanding of phosphorus dynamics and their impact on the abundance and various traits of Mazri across different climatic zones. By combining spatial and morphological data with multivariate analyses, we have demonstrated phosphorus concentration and Mazri distribution patterns, which will help in sustainable management and conservation. A more integrative approach for Mazri would be invaluable, combining long-term species monitoring and experimental and genomic manipulations and focusing on the genetic basis of phosphorus use efficiency and drought tolerance. These efforts will be pivotal to sustainable management practices and account for the resilience of these keystone palm forests to ongoing climatic changes.

5. Conclusions

Phosphorus plays a vital role in shaping the functional ecology of *Nannorrhops ritchieana* (Mazri) forests, but environmental conditions strongly influence its effects. Our results show that soil phosphorus levels are highest in areas with moderate rainfall and temperatures (NDMZ, WDMZ, and SPMZ), suggesting that climatic factors enhance phosphorus cycling. In contrast, the EWZM, with lower soil phosphorus, supports younger and more sparsely distributed Mazri populations. Although phosphorus alone did not affect forest distribution, it was linked to larger leaf size, a broader canopy, and better plant health in nutrient-rich areas. These traits reflect the ability of a species to adapt to different soil and climate conditions. Since this study focused mainly on Mazri, the analysis of other vegetation was limited. However, observational data suggest that relatively high phosphorus levels could also affect the presence of co-occurring species such as *A. modesta* and *C. decidua*. Future research involving species interactions, nutrient analysis, and long-term monitoring will help enhance conservation and management strategies. Understanding how phosphorus interacts with climate factors is crucial for selecting appropriate sites and preserving the resilience of these important palm forests amidst environmental changes.

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