Linking Forest Diversity, Structure and Functions along the Climate and Soil Conditions across Pakistan

By

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Department of Plant Sciences,

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Islamabad, Pakistan

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A thesis submitted to the Quaid-i-Azam University in partial fulfillment of the requirements for the Degree of Doctor of Philosophy

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DEDICATED TO

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List of Abbreviations

Abbreviation	Full form
AGE	Aboveground Biomass
AGFI	Adjusted Goodness of Fit Statistic
AIC	Akaike Information Criteria
BT	Big Tree
Ca	Calcium
CFI	Comparative Fit Index
CNP	Carbon Nitrogen Phosphorous
Co	Cobalt
CO2	Carbon Dioxide
Cr	Chromium
Cu	Copper
CWM	Community weighted traits mean
DTCF	Dry Temperate Conifer Forest
DTPGF	Dry Temperate Pure Pinus gerardiana Forest
DTQF	Dry Temperate *Quercus* Forest
GDP	Gross Domestic Product
GFI	Goodness of Fit Statistic
GIS	Geographical Information System
Mg	Magnesium
Mn	Manganese
MP	Mean Precipitation
MRH	Mean Relative humidity
Mt	Mean temperature
MT	Medium Tree
MTMF	Moist Temperate Mix Forest
MWP	Mean Wind Pressure
Na	Sodium
NFI	Normed Fit Index
Ni	Nickel
OM	Organic matter
P	Phosphorus
SD	Shannon diversity
SEM	Structural Equation Modeling
SMP	Soil macro properties
SmP	Soil micro properties
SR	Species Richness
SRMR	Standardized Root Mean Square Residual
SSD	Stand Structure Diversity
ST	Small Tree
STBLF	Sub-tropical broad-leaved Forest
STTF	Sub-tropical Thorn Forest

Publications arising to date from this Dissertation

The following papers have been published based on some results presented in the thesis:

1. Ali et al. (2023). Relative Humidity, Soil Phosphorus, and Stand Structure Diversity Determine Aboveground Biomass along the Elevation Gradient in Various Forest Ecosystems of Pakistan. *Sustainability*, *15*(9), 7523……………………………….253
2. Ali et al. (2022). Carbon sequestration potential of different forest types in Pakistan and its role in regulating services for public health. *Frontiers in Public Health*, *10*.254
3. Ali et al. (2022). Carbon sequestration potential of reserve forests present in protected national parks. *Journal of King Saud University-Science*, 101978……………...….255

Book Chapter

1 Dryland agroforestry; mitigating role in reducing air pollution and climate change impacts Ali et al. (2023). Chapter in agroforestorey for carbon and ecosystem management *Elsevier book*…………………………………………………256

Conference Abstract

1 Shujaul Mulk Khan[1] and Shahab Ali[1]. Assessment of Aboveground Carbon stock in the Woody Vegetation: A Case study in the Kirthar Range Sindh, Pakistan (*Climate Change and Traditional Agriculture Pattern in Pakistan: Implications and Solutions"* on dated 26-28, October 2021)………………………………………257

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Abstract

In recent decades the relationships between forest diversity, structure, and function have been one of the major topics in the field of ecosystem functioning research. The relationship between forest diversity, structure, and function might vary in different ecosystems. The Variation is not only because of the natural processes and anthropogenic disturbance but is great because of changes in environmental conditions i.e. climate and soil. To understand the effect of various climatic and soil conditions on forest diversity, structure, and function it is important to predict how forests will respond to global environmental change and influence forest function and services. At a small or local scale forest diversity, structure, and function might not be determined by climatic conditions e.g. temperature and precipitation but might be determined by topographic and soil conditions. At large regional scale forest diversity, structure, and function might be greatly associated with climatic conditions and less extent to soil conditions. In the current research work, we evaluate the relationship between forest diversity structure and function along the climate and soil conditions across Pakistan. We collect forest inventory data from 220 forest plots and use the structure equation model a powerful integrative tool to evaluate the relationship between forest diversity structure and function along the climate and soil conditions across six forest types of Pakistan i.e., sub-tropical thorn forests, sub-tropical broad-leaved forests, moist temperate mix forests, dry temperate conifer forests, dry temperate *Quercus* forests, and dry temperate *Pinus gerardiana* (Chilgoza) forest**.** The objectives of the current study are as follows; (1) to describe the relationship between Environment, Diversity, and Aboveground Biomass (AGB). (2) Relationship between, stand structure diversity, and aboveground biomass in single and multi-species forests. (3) To clarify the role of big trees in the natural forest ecosystem of Pakistan. (4) To understand the role of multiple biotic and abiotic drivers of aboveground biomass in the natural forest ecosystem of Pakistan. (5) To disentangle the carbon sequestration and its biotic and abiotic determinants in different forest ecosystems of Pakistan. The findings underscore the significant impact of climatic and soil conditions, topography, and stand structure diversity on AGB and carbon sequestration. Favorable climates, characterized by higher precipitation and moderate temperatures, along with nutrient-rich soils, are identified as key contributors to increased AGB. Stand structure diversity, particularly Shannon diversity, is highlighted as a facilitator of aboveground biomass productivity, emphasizing the positive influence of both overstorey and understory diversity. The study reveals that single and multi-species forests respond similarly to aboveground biomass dynamics, with big trees positively affecting AGB but potentially limiting the growth of other trees. Topographical factors, such as isolation, play a role in the distribution of big trees, impacting AGB dynamics. Biotic variables, including community-weighted traits mean and stand structure diversity, emerge as crucial determinants across forest types. Abiotic variables, such as soil composition and climate, interact with biotic determinants to influence aboveground biomass. Soil micronutrients and precipitation are identified as major contributors to biomass productivity, while soil macronutrients, wind pressure, and relative humidity have adverse effects in terms of carbon sequestration, climatic factors, especially temperature, precipitation, relative humidity, and wind pressure, play substantial roles, with soil characteristics, particularly in harsh climates, significantly contributing to carbon sequestration. Overall, our study provides comprehensive insights into the complex relationships shaping forest ecosystems in Pakistan, shedding light on the role of diversity, structure, and environmental factors in determining aboveground biomass and carbon sequestration. Based on the current research more detailed studies are required to investigate the complex relationship between forest diversity structure and function in different forest ecosystems of Pakistan.

Chapter 1

Introduction

Globally, forests cover approximately 4.03 billion hectares, constituting over 30% of the Earth's total surface. They play a significant role in the planet's health, contributing to 75% of terrestrial gross primary productivity (GPP) and they harbor 80% of Earth's total plant biomass. Remarkably, forests store more carbon in their biomass and soils than the amount present in the atmosphere itself (Pan et al. 2011a; Beer et al. 2010). Beyond their ecological importance, forests deliver indispensable ecosystem services to humanity. These encompass provisions like food, and raw materials, such as wood and medicine, as well as essential intangibles like clean water, spiritual and aesthetic inspiration, and climate stabilization (Jackson et al. 2005; McKinley et al. 2011). Notably, more than 200 million people living under impoverished conditions rely directly on forests for their energy, shelter, and livelihood. Forests exhibit a global presence, spanning various regions. Asia, including Asian Russia, claims the largest portion, covering 31% of Earth's forested area, followed by South America at 21%, Africa at 17%, North and Central America at 17%, Europe at 9%, and Oceania at 5% (Gorg et al. 2010; Alexandratos 2010). Approximately 5% of the world's forests are designated for commercial purposes through plantations. Forests predominantly cover the northern Hemisphere, which houses larger landmasses. The distribution of forests aligns closely with the latitudinal gradient, primarily influenced by climate factors (Woodward 1987). The duration of the growth season varies, ranging from a year in the lush tropics to merely 7 to 10 weeks in the colder boreal region. Different types of forests, characterized by deciduous, evergreen, needle-leaved, and broad-leaved trees, have adapted to the local temperature and rainfall patterns in their respective areas (Woodward et al. 2004). Several key climate variables, such as temperature and precipitation, have been employed to elucidate the global distribution of forests due to their correlation with forest spatial patterns (Holdridge 1967; Whittaker 1975). Trees sensitive to cold temperatures, particularly in tropical regions, can face mortality when exposed to minimum temperatures of 10°C. Nonetheless, certain deciduous broadleaf forests in the north can endure extreme cold, even below -40°C, by safeguarding latent tissues like buds through a process called supercoiling (Sakai 1982; Woodward 1987). Precipitation has a more direct impact on forest distribution compared to temperature (Woodward et al. 2004). Along with gradients from forested areas to deserts, the availability of water plays a crucial role. When trees cannot meet their transpiration needs due to limited water, they give way to shrubs or grasses (Calder 1998). Drought poses a significant threat, resulting in the decline or death of mature trees and hindering the establishment of new seedlings (Van der Molen et al. 2011). Broadly, the furthest extent of forest distribution is contingent upon a minimum annual precipitation of 600 mm, except for colder regions where this limit drops to 400 mm due to lower evaporation rates (Woodward 1987).

1.1. Forest diversity, structure and functioning in the changing world

Biological diversity research and conversations have emerged from the obscurity of fundamental scientific discourse over the last decade to become one of the most pressing and significant concerns in environmental policy. This 180-degree turn has elicited varied reactions from the scientific and forestry communities. While many ecologists are pleased that ecological issues are again on the political agenda, they face challenges in transitioning from academia to the real world of resource management, economics, and politics. Many foresters have struggled to accept that biodiversity, which formerly had no commercial value, could influence how they manage forests. However, market pressure requiring forestry to manage biodiversity quickly compelled forestry to prioritize biodiversity preservation. Concerns about dwindling biological diversity have numerous sources, only some of which are considered scientific. One of the key ecological arguments for maintaining biodiversity is that biodiversity loss may hamper life-sustaining processes required by people, such as primary productivity, carbon storage, water retention, and the provision of clean water. Ecological stability may be associated with diversity. Keeping diversity may thus be crucial for long-term sustainability. These are old unresolved ecological concerns, and contemporary disputes have not resolved them. Many poor countries wanted some degree of control over the mostly undiscovered biological richness in the tropics, making the economic rather than ecological rationale for preserving biodiversity a driving force behind the Biodiversity Convention in Rio in 1992. Other motivations to conserve biodiversity include ethical considerations and the enjoyment that many people get from having a diverse environment. Characterizing the structure of forests involves assessing the traits and attributes of individual structural elements, as well as understanding the spatial arrangements in both horizontal and vertical dimensions (Franklin et al. 2002). Due to the intricate three-dimensional nature of forests, they encompass diverse vertical and horizontal structural characteristics. Conventionally, ecologists have measured forest structure components within limited sampling regions (McElhinny et al. 2005). However, advancements in remote sensing technology in recent years have significantly bolstered our capacity to evaluate critical forest structure variables, such as tree height and leaf area, across extensive areas. Numerous investigations have demonstrated a strong correlation between the complexity index of stand structure, as determined by aerial light detection and ranging (LiDAR), and field data. This suggests that LiDAR holds the potential for broader application in advancing our comprehension of global forest structure (Kane et al. 2010; Næsset 2002). The principal drivers of changes in forest structure, the configuration of landscape patterns, and the initiation of conditions conducive to successional dynamics and structural evolution are disturbances (Swanson et al. 2011). Structural evolution is often categorized into stages based on stand ages and levels of structural complexity (Franklin et al. 2002). For instance, mature stands frequently exhibit elevated structural complexity due to horizontal diversification and processes shaping and occupying canopy gaps. The intricate interplay of species diversity and variations in tree sizes contributes to this structural complexity. Such complexity can be evaluated through multivariate analyses that encompass an extensive array of structural variables and geographical data (McElhinny et al. 2005).

The approach utilizing indices is also employed to integrate observed structural attributes of forests with LiDAR data and high-resolution multispectral aerial photography. This fusion aids in mapping the intricacy of forest structure or comprehending patterns in connection with environmental factors (Pasher & King 2011). Remote sensing-based structural indices serve purposes like identifying successional stages, evaluating the diversity of forest structures, and establishing criteria for both forest management and species conservation. Notably, the age of a forest, or the interval since its last disturbance, constitutes a crucial facet of its structure. Analysis of age distribution reveals that, particularly in boreal and temperate zones, a majority of forests have experienced natural disruptions such as wildfires or land management activities over the past century. While all woodlands undergo some degree of natural disturbances (and many encounter human-induced disruptions), the frequency of disturbances typically inversely correlates with their intensity. For instance, in Amazonia, a standard 1-hectare plot experiences annual mortality due to disturbances, but significant stand-initiating disturbances arise only at intervals spanning thousands or tens of thousands of years (Espírito-Santo et al. 2010). Throughout history, forests have predominantly served as sources of natural resources. Globally, forests have been exploited for both timber and non-timber products, with forest plantations largely dedicated to this purpose. The sustained economic productivity of biomass hinges on several parameters determining nutrient and energy balances, as well as interactions within the ecosystem's food chain. The notion of sustained economic productivity in forests entails a degree of human impact on the ecosystem. The nature of these impacts varies depending on factors like the utilized product (e.g., timber, resin, pasture) and the manner of utilization (e.g., coppice, high forest, clear-cut). Therefore, a corresponding array of ecological traits is necessary for withstanding these impacts. In regions where natural hazards pose consistent threats to human populations, goods, and infrastructure, the protective function of forests becomes paramount. This safeguarding function extends to a wide array of perils, including torrential flows, avalanches, water and wind-induced soil erosion, groundwater and spring water contamination, desertification, and more. Tailored strategies must be devised for each forest management scenario to counteract the susceptibility to subsequent natural forces. The pivotal ecological attributes for protective forests may shift according to the specific hazard to be averted, differing significantly from those essential in the context of productive forest ecosystems. Increasingly, forests are becoming recreational spaces for urban residents. However, frequent visits bear diverse consequences, including persistent disturbances to deer populations, soil compaction, pollution, heightened forest vulnerability, and others. Forests designated primarily for recreational use must ensure accessibility and adhere to specific aesthetic criteria (Willis & Benson 1989). In contrast to productive and protective forests, visitor comfort and safety standards might take precedence over other management objectives. Lastly, forests provide habitats for a substantial portion of our flora and fauna, demanding preservation efforts to uphold biodiversity. Previously managed forest areas are being reverted to their natural state to safeguard endangered plant and animal populations. The trajectory of natural forest reserves post the cessation of management practices hinges on the specific attributes and health of the ecosystem. Beyond the ecosystem services mentioned earlier, human well-being derives benefits from various environmental impacts of forests, such as climate regulation, scenic beauty, hydrological balance, water and air quality, CO_2 absorption, and aesthetics. Several natural and human-induced stressors exert influence on these broad environmental functions. The capacity to withstand these stressors is determined by the inherent characteristics of the ecosystem, which define the course of biological responses and the system's resilience against external pressures, like the 'critical load' of acid depositions. For each forest function, distinct and ecosystem-specific attributes need to be upheld. Neglecting these can lead to degradation or even decline of forest ecosystems (F hre r 99) . Historical failures in preserving forest functions often resulted from ecologically excessive exploitation of forests during multifaceted use (Glatzel 1991). For instance, numerous protective forests in the Alps are presently in a degraded state due to their extensive utilization in the past. Simultaneous activities like timber harvesting, agriculture (grazing), high deer populations from hunting, and, to some extent, winter tourism, collectively surpassed the ecosystem's capacity to maintain the necessary qualities for its protective function (Mayer 1976).

It's evident that a forest's capacity to deliver services is limited to the capabilities of its specific ecosystem. When designating a particular forest area for a specific purpose, two key steps are crucial: (1) defining the unique ecosystem-related requisites for that purpose, and (2) evaluating the ecosystem to determine if it possesses the necessary attributes to fulfill these requisites. In cases of incompatibility, two approaches can be taken: intervening with corrective management measures or adapting the intended forest function to align with the ecosystem's potential. Both these methods are employed in forestry, yet their efficacy in maintaining forest functions hinges on the degree to which they are informed by scientifically robust knowledge. Forests serve a multitude of socio-economic objectives, each catering to the diverse needs of human populations. Particularly in Europe, scientific inquiry into forest ecosystems is primarily geared towards supporting forestry, and this research must account for the range of these distinct needs. In essence, most scientific inquiries arise to address the function-related diversification of forest management. The economic dimension, involving timber and non-timber resource production for personal or commercial utilization, remains a predominant concern globally. While historically the recreational aspect of forests was of limited prominence, contemporary perspectives recognize the importance of supporting aesthetic and recreational purposes as key forestry goals (Dieterich 1953). In practice, the majority of forests possess multi functionality, providing both economic and societal benefits to varying extents. However, specific roles often necessitate different management approaches due to their functional specialization (e.g., protective forests, short rotation plantations, energy plantations, etc.). The direction of commercial forestry is increasingly inclined towards this kind of differentiation. The assortment of criteria linked with distinct forest functions underscores the importance of integrating ecosystem considerations into forest management within the context of their intended functions.

1.2 Current state of knowledge: Forest diversity, structure and functioning

Forests play a crucial role in supporting more than two-thirds of terrestrial biodiversity and contributing to 44% of the global forest carbon stock. Recent progress in the realm of biodiversity and ecosystem functioning research has been marked by two significant developments. Firstly, there has been a convergence and increased overlap of two ecological disciplines that previously examined the "essence" of ecosystems separately: population or community ecology and ecosystem ecology (Pan et al. 2011; Schulze and Mooney 1993; Kinzig et al. 2002b; Loreau et al. 2002; Likens 1992; Grimm 1995). Secondly, closely linked to the first aspect, a novel synthetic ecological framework has emerged. This framework accentuates the dynamic participation and diversity of biota in influencing environmental conditions within ecosystems, extending even to global processes (Lawton 2000; Loreau et al. 2001; Naeem 2002; Haywood 2007). Community ecology has directed its focus towards examining the interplay between biotic factors (interactions among species like competition or predation) and abiotic factors (physical and chemical conditions) to enhance our understanding of biodiversity. Illustrative instances from woodland ecosystems include (1) The noticeable increase in the diversity of tree species along latitudinal gradients, spanning from boreal to tropical regions (Ricklefs 1977), or even within the same continent (Silvertown 1985). This diversity pattern suggests variations arising from historical periods without substantial climate changes, concurrent shifts in physical parameters like temperature and moisture, or a range of other factors (Pianka 1966; Stevens 1989); (2) The discernible distinction between late-successional species and highly diverse early-successional woody communities. Shade-tolerant species tend to surpass light-demanding species in regions like Central Europe, leading to the development of less prosperous woodlands (Küppers 1984). On the other hand, ecosystem ecology has delved into the study of ecosystems without giving significant weight to the richness of species. Although information was typically gathered at the species level and then aggregated to encompass the entire ecosystem, the focus was placed on the flow of energy and the movement of elements in various forms (Grimm 1995). To illustrate, one instance involves the amalgamation of findings from study sites within the International Biological Programme (IBP), particularly those situated in deciduous woodlands (Khanna & Ulrich 1991; Röhrig 1991). In a similar vein, biogeochemistry has perceived ecosystems as intricate networks of interconnected compartments, rather than solely focusing on species interactions. Nonetheless, this approach has predominantly been for practical purposes rather than indicating that species traits lack significance (Schimel 2001). Nonetheless, the utilization of earth system models with limited diversity content rather than solely considering superficial features like the land surface color initially stemmed from the recognition of similarities among species in fundamental functional attributes, such as photosynthetic pathways. This realization highlighted that plant productivity is influenced by energy absorption rather than the specific identities of species (Mooney 2001).

A particular ecosystem function is assessed by considering (1) the functional characteristics of the organisms involved, (2) the interconnected biogeochemical processes, and (3) the surrounding inorganic elements, as outlined by the newly developed paradigm. This illustrates how the biota and its diversity actively shape environmental conditions. Tansley's initial depiction of an ecosystem recognized the influence of species on the physical system, yet not from the perspective of variety (Tansley 1935). The modeling community has also acknowledged the significance of biodiversity and its impact on global processes within the biosphere; with the exception of the most basic climate and ecosystem models, all incorporate the diverse functional plant types distinguished by their morphological and physiological properties (Schimel 2001; Schulze & Schimel 2001), such as "broadleaf tree," "needleleaf tree," "C3 grass," "C4 grass," or "shrub," for instance. Cox and colleagues (2000) have noted these transformations in forest cover and condition, and their implications are deeply concerning. These changes bear relevance for biodiversity preservation and a range of essential ecosystem services furnished by forests, including pollination, climate regulation, biomass production, water purification and supply, and the provision of habitats for forest species (Bauhus et al. 2010; Brockerhoff et al. 2013; Decocq et al. 2016; Liang et al. 2016). Furthermore, there is a growing body of evidence indicating a linkage between the provision of ecosystem services and the facets of biodiversity; biodiversity and the majority of ecosystem services exhibit a positive association (Hooper et al. 2005; Balvanera et al. 2006; Isbell et al. 2011; Gamfeldt et al. 2013). Diverse processes have been proposed to elucidate the correlation between biodiversity and environmental services. It is anticipated that there will be a presence of niche complementarity in both time and space, along with functional effect trait complementarity and functional response trait complementarity (Isbell et al. 2011). Specific combinations of trees have demonstrated enhanced growth when particular plant species are cultivated together. For instance, nitrogen-fixing tree species may stimulate the growth of other tree species in mixed stands within nitrogen-limited environments Forrester and Bauhus 2016; Thompson et al. 2014). The diversity of forests and trees bolsters their resilience against disturbances, which diminishes or dilutes resources (e.g., for herbivores), alters trajectories, and amplifies trophic interactions (such as increased abundance and activity of natural enemies) (Jactel et al. 2017). Additionally, the "sampling effect" can enhance the provision of ecosystem services simply because communities with greater species richness are more likely to encompass species that exhibit faster growth, greater resilience to specific disturbances, or other advantageous traits that enhance ecosystem functioning or service delivery (Wardle 2001; Lefcheck et al. 2015). Recognizing the significance of biodiversity in furnishing ecosystem services, the extensive degradation of forests is anticipated to result in far-reaching consequences, including reduced resistance (or heightened susceptibility) to natural or human-induced disturbances. These anomalies appear to be growing in frequency and severity (Pachauri et al. 2014; Brockerhoff & Liebhold 2017; Freer-Smith & Webber 2017). Projected reductions in biodiversity are expected to diminish forests' capacity to withstand challenging climates, invasive species, diseases, pests, and other disruptive factors, consequently leading to an overall decline in the provisioning of ecosystem services (Isbell et al. 2015; Jactel et al. 2017).

The biodiversity found within the canopy trees and other species in planted forests often falls short compared to that in "natural forests" or mixed-species forests. Consequently, their capacity to fulfill certain ecological roles is likely to be compromised. For instance, mixed forests tend to excel in performing a diverse array of provisioning functions, exhibiting greater resilience against various pressures when contrasted with forests composed of a single species (Jactel et al. 2017; Barlow et al. 2007; Brockerhoff et al. 2008; Gamfeldt et al. 2013; Forrester & Bauhus 2016). These connections between different forest types, biodiversity, and ecosystem services hold paramount importance in guiding forest management and policy decisions. Nevertheless, due to the multitude of ecosystem services, making broad assertions about the role of forest diversity proves challenging. Furthermore, there are trade-offs among distinct ecosystem services that hinge on the composition of tree species and the type of forest stand. While certain combinations of trees, or even forests dominated by a single species, excel in providing specific services, others excel in delivering different services (van der Plas et al. 2016). Hence, comprehending the intricate connections between biodiversity and crucial ecosystem functions like aboveground biomass (AGB) or carbon (C) storage and productivity in natural forests becomes imperative for anticipating the repercussions of biodiversity loss on ecosystem operation and services (Cardinale et al. 2012; Forrester & Bauhus 2016). Historically, a majority of research has unveiled a positive correlation between species diversity and ecosystem functions across varying forest types and biomes. Numerous investigations have established a relationship between ecosystem performance and taxonomic, functional, or phylogenetic diversity (Cadotte et al. 2008; Cavanaugh et al. 2014; Liang et al. 2016). However, our understanding remains limited concerning the relative significance of diverse biodiversity indicators, stand structural characteristics, and environmental circumstances on aboveground carbon storage in natural forests, especially when accounting for the impacts of disturbance intensities. It's noteworthy that the world's forested areas are diminishing due to human-induced disturbances (e.g., logging), which has raised serious concerns about the loss of biodiversity and ecological functioning (Asner et al. 2009; Thom & Seidl 2015). Disturbance intensities, for instance, exert a profound influence on the relationships between species diversity and aboveground biomass across different biomes. In line with the intermediate disturbance hypothesis, intermediate levels of disturbance uphold maximal diversity, leading to a curvilinear connection between species diversity and ecosystem performance (Yeboah & Chen 2016). Despite various factors influencing aboveground C storage, there has been limited exploration into whether the relevance of these factors varies with disturbance intensity (Jucker et al. 2016; Paquette and Messier 2011).

The relationship between biodiversity and ecosystem functioning is explained through two main hypotheses: the niche complementarity hypothesis and the mass ratio hypothesis. These hypotheses, while not mutually exclusive, shed light on the mechanisms at play. The 1st hypothesis (niche complementarity hypothesis) suggests that having a diverse range of species or functional traits can enhance ecosystem processes. This leads to improved biomass productivity due to the efficient use of resources by different species or interacting individuals. This efficiency results from the partitioning of ecological niches and facilitation among species. Recent studies indicate that functional trait and phylogenetic diversity measures are more accurate predictors of aboveground biomass or productivity than species richness. This is because they better reflect the extent of functional overlap and redundancy among species (Paquette & Messier 2011). On the other hand, the 2nd hypothesis (mass ratio hypothesis), suggests that ecosystem functions are predominantly influenced by the traits of the most dominant species over time. This means that higher carbon storage above the ground could be directly linked to the functional characteristics of these dominant species. Evaluating functional trait composition or identity, such as the community-weighted mean of a specific trait, helps assess the functional qualities of these dominant species. This approach is based on the idea that the traits of these dominant species play a pivotal role in shaping ecosystem functions (Grime 1998; Cavanaugh et al. 2014; Tobner et al. 2016; Ali et al. 2017). Understanding how the interplay between these two systems changes in different scenarios has the potential to enhance forest management practices and strategies for conserving biodiversity (Ratcliffe et al. 2016). For instance, the varying significance of the mass ratio effect on tree growth at the extreme latitudinal points of the European continent implies that specific traits play crucial roles in forests subjected to harsh climates. Conversely, in Mediterranean forests constrained by water availability, niche complementarity strongly bolsters ecosystem functioning (Ratcliffe et al. 2016). Measuring the inequality or diversity of tree sizes within stands using indicators like tree heights or diameters at breast height (DBH) is a common approach to describing stand structural characteristics (Pretzsch 2014). In natural forests, competition among different species and within the same species for resources significantly influences stand structure. This competition provides insights into the practical level of species complementarity achieved through niche differentiation and facilitation (Yachi & Loreau 2007; Zhang & Chen 2015). Recent studies propose that the diversity in stand structure, specifically in terms of tree DBH and height, holds greater importance than species diversity in enhancing aboveground carbon storage, biomass, and production in natural forests. Conversely, contrasting research suggests that increased stand heterogeneity might lead to a reduction in aboveground biomass or productivity. However, the nature of these interactions varies across different types of forests—natural, planted, and experimental adding complexity to the overall picture (Binkley et al. 2010).

1.3 Relationships between taxonomic diversity and forest functioning

For over thirty years, the correlation between biodiversity and ecosystem functioning has been a subject of ongoing scientific discourse. As the transformations brought about by habitat loss, species introductions, and climate fluctuations reshape ecological communities, the importance of delving deeper into this correlation and its fundamental mechanisms becomes increasingly evident (Grime, 1973; Adler et al., 2011). Through controlled experiments designed to manipulate local diversity levels, insights have emerged regarding the relationships within grassland systems. These experiments have revealed positive associations between plant diversity and production on a plot-by-plot scale (Tilman et al. 1997; Hector et al. 1999). Nevertheless, when examining the connections between biodiversity and ecosystem function in natural systems through meta-analyses, the findings have been inconsistent. Some researchers observe that the relationships between species richness and biomass or production often exhibit a hump-shaped pattern, while others contend that positive associations are more prevalent (Gillman & Wright 2006). Detractors of these comparative analyses argue that the divergence in conclusions stems from methodological disparities in field studies, particularly variations in sample unit size and spatial extent. Consequently, suggestions have been put forth to establish worldwide networks that adhere to standardized and uniform approaches to mitigate these discrepancies (Condit 1995; Adler et al. 2011; Chase & Leibold 2002; Whittaker & Heegaard 2003). Considerable debate has centered around the driving forces behind the impact of diversity, whether it arises from niche partitioning and facilitation (referred to as the complementarity effect) or the dominance of one or more highly productive or high-biomass species (known as the selection effect) (Loreau & Hector 2001; Cardinale et al. 2012; Tilman et al. 1997). The complementarity effect theory posits that a diverse array of species possesses a broader spectrum of functional traits, enabling them to make more efficient use of limited resources. This enhanced resource utilization enhances overall ecosystem functioning when compared to less diverse populations. Conversely, the selection effect hypothesis contends that ecosystem functioning is propelled by dominant species or traits, and the favorable relationships between biodiversity and ecosystem function emerge primarily because diverse communities are more likely to include species and traits that excel in performance. A more comprehensive understanding of how diversity and dominance jointly influence ecosystem function would greatly assist in formulating conservation and restoration strategies for ecosystems that are under threat or are being exploited.

To comprehensively examine the interactions between biodiversity and ecosystem function across forest ecosystems on a continental scale, particularly concerning productivity and/or aboveground carbon storage, diverse methodologies have been employed. These approaches encompass inquiries into the individual contributions of species to the overall functioning of the community, along with the utilization of ecosystem function models to explore various scenarios of local extinctions (Bunker et al. 2005; Balvanera et al. 2005). Analyzing resampled data to scrutinize the connection between specific characteristics and function, as well as conducting multisite investigations that establish links between biodiversity or functional attributes and ecosystem function, are strategies that have been employed (Baker et al. 2004; Vilà et al. 2007; Baker et al. 2009). Instances of research involving data resampling to investigate the relationship between features and function, as well as multisite studies that establish connections between biodiversity or functional traits and ecosystem function, can be observed (Vilà et al. 2007; Paquette & Messier 2011). Caspersen and Pacala (2001) uncovered a connection between aboveground biomass, successional stage, and species richness in temperate forests across the Midwestern United States. This finding lent support to the complementarity mechanism. An investigation spanning six hectares of old-growth forest in Panama revealed that tree species richness played a more significant role in explaining variations in carbon storage than tree dominance, thus strengthening the case for the complementarity process (Ruiz-Jaen & Potvin, 2010). Nevertheless, models have demonstrated that fluctuations in aboveground carbon storage are contingent on the specific species being eliminated. Moreover, stand-level factors like basal area and wood density align with regional trends in aboveground biomass observed in the Amazon and Asia (Baker et al. 2004; Slik et al. 2010). These observations give weight to the selection effect hypothesis, which posits that a select few dominant species disproportionately contribute to carbon storage. Conversely, some studies have not found a consistent correlation between wood density and forest biomass. They have also unveiled discrepancies in relationships between diversity metrics and carbon storage even in geographically proximate forests (Ruiz-Jaen & Potvin 2011; Balvanera et al. 2005). Numerous potentially pertinent site-specific attributes, such as local climate, often remain unaccounted for in many of these multisite investigations, possibly obscuring critical connections. Additionally, due to logistical constraints, several multisite experimental and observational studies involve small plot sizes and/or limited spatial extents, potentially resulting in an underestimation of the influence of diversity on ecological processes (Cardinale et al. 2011; Ma et al. 2010).

1.4 Relationships between functional trait diversity and forest functioning

Hence, the relationship between biodiversity and ecosystem functioning has become a central topic in ecology (D az & Cabido 2001; Tilman 1997), albeit one that continues to be vigorously debated (Hooper 2005). Despite its significance within biodiversity, a standardized definition of functional diversity is currently lacking. Terms like "functional diversity within the community," "the value, range, and relative abundance of traits of organisms in a community," "the variation or distribution of traits in an assemblage," and "biodiversity components' impact on ecosystem working or functioning" have been used to encapsulate the concept (D az & Cabido 2001). Similarly, functional diversity has been characterized as "the distribu tion and range of functional traits of the organisms present in a community or ecosystem" (Petchey & Gaston 2006). Broadly, definitions of functional diversity can be classified into two main categories. The first regards the organism as a unit and centers on the quantity and attributes of the organism, encompassing concepts like the diversity of functional groups. The second treats the trait as the primary unit and emphasizes the spectrum and dispersion of traits, incorporating the notion of functional trait diversity. Notably, the attention dedicated to the diversity of functional traits is on the rise (Hillebrand & Matthiessen 2009; Schleuter et al. 2010). The concept of functional diversity may seem straightforward, yet researchers have sought various ways to quantify it. A common method for assessing functional diversity is through the richness of functional groups (Schleuter et al. 2010). However, when functional groups exhibit minimal differences, this approach can lead to an overestimation of functional redundancy. Walker et al. expanded on the idea of functional diversity by introducing an aggregate measure that employs species attributes. The simplest functional diversity index involves calculating the sum of Euclidean distances between all pairs of species within a given assemblage. However, this metric's accuracy heavily relies on species richness (Wright et al. 2006). To address this limitation, Schmera and colleagues (2017) suggested normalizing the distance matrix by the number of functional units. As our comprehension of functional diversity has deepened, various metrics have emerged over time. These include metrics like species abundance weight (e.g., the community-weighted mean CWM), functional divergence, functional regularity, multiple traits, intraspecific variation, and numerous others. Additionally, Petchey and Gaston introduced the concept of a functional dendrogram, which utilizes multi-trait distances for computing functional diversity (Schleuteret et al. 2010; Mouillot et al. 2005). Cornwell devised an index that employs the volume of the trait space's convex hull as an alternative to the distance matrix (Cornwell et al. 2006). Much like species diversity, functional diversity consists of three main components: functional richness, evenness, and divergence.

1.5 . Relationship between functional diversity and species richness

The relationship between functional richness and species richness prompts inquiries into how to effectively assess their distinct roles in ecosystem functioning. Often, functional diversity demonstrates a positive connection with species richness, potentially leading species richness to serve as a surrogate for functional richness (Tilman, 2001; Cadotte et al. 2011). Adler and colleagues (2011) observed that a definitive connection between species richness and productivity was absent at the levels of individual sites, regions, and even globally. Due to species overlap and variations within species, the species richness observed in natural ecosystems might be either higher or lower than the functional diversity present. The concept of "selection effects" explains the strong positive association between functional diversity and species richness (dle r et al 2 ; D az abido 2). This hypothesis posits that as the regional species pool expands, the value or scope of traits also increases randomly. However, this favourable correlation has rarely been thoroughly investigated in real-world ecosystems (D az abido 2). Various factors intrinsic to natural communities, such as functional redundancy, local species pools, environmental filters, and more, could influence the connection between diversity and ecosystem performance. A study by Mayfield et al. revealed that alterations in land use can lead to eight distinct trajectories for both functional diversity and species richness (Mayfield et al. 2010). Natural ecosystems often exhibit a higher degree of complexity. For instance, in a study conducted across 24 small streams within boreal forests in Ontario, Canada, researchers observed that the associations between functional diversity and species diversity varied across a spectrum from positive to negligible under different disturbance levels. Additionally, the strength of disruption significantly influenced the slopes of these associations. While Flynn et al. found that plant functional diversity and species richness remained relatively stable despite changes in land use intensity, the relationship between functional diversity and species richness displayed notable shifts between forested and deforested habitats. The intricate nature of this relationship is further influenced by factors like the number of functional traits and their attributes, the significance of specific functional traits, the methodologies employed for calculating functional diversity indices, and various other determinants (Biswas & Mallik 2011).

1.6 Ecosystem functioning

Plant productivity and biomass have commonly been employed as indicators of ecosystem functioning. Productivity is a fundamental aspect of ecosystems and lends itself relatively easily to quantification. Ecologists have employed various metrics to gauge ecosystem functioning, such as light interception, soil moisture, soil carbon and nitrogen content, nitrogen mineralization, and litter breakdown (Craine et al. 2002; Griffin et al. 2009). Costanza et al. illustrated that ecosystem functioning is intricately tied to ecosystem habitats, biological or ecological attributes, and processes. It governs the cycling of materials, the flow of energy, and the transmission of information (Hooper et al. 2005). Pacala and Kinzig (2002) categorized ecosystem functioning into three dimensions: energy and material stocks, fluxes in energy or material processing, and temporal stability in rates or stocks. Stability encompassed both resilience and resistance (Srivastava & Vellend 2005; Pacala & Kinzig 2002). Giller and colleagues argued that ecosystem functioning should also encompass ecosystem values. Ecosystem functioning plays a crucial role in providing products and services to humans. Some ecologists argue that ecosystem functioning aligns closely with ecosystem services, with some considering ecosystem functioning to encompass ecosystem services as well (Jax 2005; Gamfeldt et al. 2008). Nevertheless, ecological functioning and ecosystem services are intricately linked. Costanza et al. categorized ecosystem services into 17 distinct categories, each corresponding to a specific facet of ecosystem functioning. They emphasized that ecosystem services and ecosystem functioning are not synonymous, rather, ecosystem services are directly or indirectly derived from ecosystem functioning, and diverse ecosystem functions are interrelated (Costanza et al. 1997). Recent research highlights that functional diversity recognizes the capacity of ecosystems to adapt their services within the context of global environmental changes (Díaz et al. 2007).

1.7 Relationships between functional trait composition and forest functioning

Functional traits serve as a valuable tool in this context, as they embody trade-offs that dictate species performance within a given environment. Consequently, these traits influence the distribution of species across environmental gradients (Engelbrecht et al. 2007; Cornwell & Ackerly 2009; Swenson et al. 2012). The assessment of functional traits for coexisting species offers an opportunity to differentiate between the indications of deterministic and stochastic assembly processes within communities (e.g., Kraft et al. 2008; Cornwell & Ackerly 2009; Ingram & Shurin 2009). Several recent investigations have utilized functional traits to explicitly showcase the role of environmental filtering in shaping the composition of species-rich tropical forests (Ter Steege et al. 2006). However, some of these studies have focused on a limited set of functional traits or a restricted number of species while others have been conducted on relatively small geographic scales or within constrained habitat ranges (Paine et al. 2011). Consequently, the degree to which environmental filtering leads to predictable shifts in community functional composition across wide-ranging environmental gradients on a large scale remains uncertain, particularly in highly diverse tropical forests (Malhi et al. 2008). A more comprehensive understanding of this matter is pivotal to enhancing prognostications regarding how community functional composition and associated ecosystem functioning will respond to global changes.

Despite ongoing debates regarding the intricate ecological mechanisms operating across local, regional, and global gradients, it remains evident that the composition of functional traits, their diversity, and the complexity of stand structures play pivotal roles in maintaining the functionality of forest ecosystems (Finegan et al. 2015). Unraveling the intricate connections between functional traits, stand structural complexity, and aboveground biomass or productivity holds paramount importance for accurate global carbon accounting. This is particularly significant as the sequestration of carbon within aboveground biomass during forest restoration stands as a cornerstone process for effectively mitigating climate change. However, further investigation is warranted to delve into the impacts of stand age-related forest attributes on aboveground biomass within the context of tropical forest succession (Lohbeck et al. 2015; Poorter et al. 2016). Forests encompass approximately two-thirds of terrestrial biodiversity, harboring a remarkable 44% of the global forest carbon reservoir. To gauge the potential impacts of biodiversity loss on both ecosystem performance and services, comprehending the intricate connections between ecosystem functions and biodiversity is paramount. This includes grasping the relationships between variables like aboveground biomass or carbon storage and productivity within natural forest settings (Pan et al. 2011; Cardinale et al. 2012; Forrester & Bauhus 2016). Spanning diverse forest types and biomes, a majority of earlier research has highlighted favorable associations between species richness and various ecosystem processes. A multitude of investigations have underscored the link between taxonomic, functional, or phylogenetic diversity and ecosystem functioning (Cavanaugh et al. 2014; Ali & Yan 2017). Nevertheless, the relative importance of different biodiversity indices, the characteristics of stand structures, and environmental factors concerning aboveground carbon storage remains a relatively unexplored domain, particularly when accounting for varying disturbance intensities in natural forest contexts. Of utmost significance, human-induced disruptions such as logging are contributing to the contraction of global forest coverage, prompting profound concerns about the repercussions for biodiversity loss and overall ecosystem health. For example, the associations between species diversity and aboveground biomass across diverse biomes exhibit a more pronounced susceptibility to the impacts of disturbance intensities (Grace et al. 2016; Yeboah & Chen 2016; Sanaei et al. 2018). Adhering to the concept of intermediate disturbance, a curvilinear relationship between species diversity and ecosystem function emerges due to the maintenance of peak diversity levels at intermediate disturbance levels. Amidst the numerous factors influencing aboveground carbon storage, there is a dearth of research investigating whether the significance of these factors varies contingent upon the severity of disturbances (Kröber et al. 2015; Jucker et al. 2016; Paquette and Messier 2011). Stand-level descriptors of tree size inequality or diversity, based on attributes such as tree heights or diameters at breast height (DBH), are commonly employed to characterize stand structural characteristics. The formation of stands in natural forests is heavily influenced by interspecific and intraspecific competition for resources (Pretzsch 2014), which contributes significantly to the stand's overall makeup. This aspect can also serve as an indicator of the extent to which species complementarity has been achieved through niche differentiation and facilitation. Recent studies indicate that stand structural diversity, encompassing tree DBH and height diversity, or the inequality in individual tree sizes, holds more pronounced importance for enhancing aboveground carbon storage, biomass, and productivity in natural forests compared to species diversity itself (Ali et al. 2016; Danescu et al. 2016). Nonetheless, other investigations have suggested that augmenting stand structural heterogeneity may lead to reductions in aboveground biomass or productivity. However, it's worth noting that the nature of these relationships could exhibit variability across different types of forests, including natural forests, plantations, and controlled experimental forest settings (Binkley et al. 2010; Ryan et al. 2010). In exploring the simultaneous influence of functional trait diversity and composition on aboveground biomass in natural forests, two contrasting ecological hypotheses emerge the mass ratio hypothesis (MRH) and the niche complementarity hypothesis (NCH) (Ali et al. 2017; Poorter et al. 2017; Yuan et al. 2018). The NCH postulates that a broad spectrum of species and functional traits enhances ecosystem performance under niche differentiation, leading to diverse resource utilization patterns within communities (Tilman 1997). In this context, aboveground biomass should exhibit a positive correlation with functional trait diversity or functional divergence (FDvar) encompassing single-trait or multivariate-trait diversity, owing to the resource-use complementarity and ecological niche specialization found in natural forests (Ali et al. 2017). Conversely, the MRH argues that ecosystem functioning is largely shaped by the functional attributes of the most abundant species within communities. Consequently, the aboveground biomass in natural forests should be closely linked to the community-weighted trait mean (CWM) (Grime 1998; Prado-Junior et al. 2016; Ali et al. 2017). Numerous studies have corroborated the predictions of both the NCH and MRH, demonstrating that the CWM of trait values governs aboveground biomass in natural second-growth tropical forests, where a small number of highly productive and functional species dominate (Ali et al. 2017; Poorter et al. 2017). However, the complex interplay between acquisitive and conservative functional strategies and their distinct impacts on ecosystem functioning, highlighting the joint importance of functional trait diversity and composition, continues to fuel the debate surrounding the role of the mass ratio effect (Ali et al. 2017). Other explanatory factors, including abiotic elements like soil properties and climatic conditions, along with stand age-related structural characteristics such as stem count and maximum diameter, contribute to the variability in aboveground biomass, alongside functional divergence and composition (Ali et al. 2016; Ali et al. 2017; Fotis et al. 2018; Poorter et al. 2017). For instance, soil texture attributes regulate the availability of water crucial for plant growth and survival, while soil nutrient levels govern resource accessibility (Paoli et al. 2005; Toledo et al. 2012; Sanaei et al. 2018). Adequate soil nutrient availability can accelerate plant development, but it may also foster competition, leading to elevated mortality and turnover rates. Furthermore, modifications in the composition and diversity of functional traits can indirectly impact aboveground biomass by altering in response to soil nutrient variations (Prado-Junior et al. 2016; Ali & Yan 2017). As an illustration, consider natural forests, where enhanced soil fertility can have a dual impact on functional trait diversity. On one hand, it can promote greater diversity by supporting a higher level of niche differentiation and facilitation among species. On the other hand, it might reduce diversity due to intensified interspecific competition for limited resource utilization. An alternative perspective, the inverse-texture hypothesis, proposes that areas with fine-textured soils (characterized by high clay loam content) in humid regions with poor drainage often exhibit elevated productivity. In contrast, regions with coarse-textured soils in arid or dry climates might struggle to maintain water availability during dry seasons (Noy-Meir 1973). Interestingly, the impact of soil textural properties on the correlations between functional trait diversity, composition, and ecosystem functioning has been scarcely explored, particularly in the context of distinguishing between intricate natural forests and grasslands (Sanaei et al. 2018). Recent investigations have shown that soil textural attributes only marginally predict biodiversity, stand structure, and aboveground biomass in extensive tropical forests. Additionally, it's plausible that during forest succession, there could be significant shifts in functional trait diversity, composition, and aboveground biomass (Becknell & Powers 2014; Ali et al. 2017). In such cases, slow-growing, resource-conserving, and shade-tolerant species might replace faster-growing and resource-demanding species (Poorter et al. 2019). Considering that old-growth forests often feature more mature and larger trees, it becomes evident that stand age-dependent structural attributes can exert substantial influence on aboveground biomass, either directly or indirectly due to alterations in functional trait diversity and composition (Becknell and Powers 2014; Ali et al. 2016; Fotis et al. 2018).

1.8 Relationships between stand structure and forest functioning

Stand structure attributes in forest ecosystems directly enhance productivity or biomass without the contribution of species diversity (Dănescu et al. 2016). Though species diversity is a component of stand structure complexity, although, trees' height, diameter, and canopy diversity combined or alone are considered as stand structure diversity. Overall, stand structure complexity, diversity, or other similar variables are considered as stand structure attributes (Dănescu et al. 2 6; Poorter et al. 2015). The relationship between stand structure diversity and forest function relationship (i) The niche complementarity hypothesis (Tilman 1999) According to Tilman, more diverse species and functional traits result from coexisting species within a community using resources effectively, which leads to improved forest functioning (Tilman, 1999). (ii) According to the selection hypothesis, the community's high probability of having only a few highly productive and functional species is explained by higher ecological performance (Loreau & Hector 2001). These theories have been publicly tested to explain how species variety affects how natural ecosystems, particularly forests, function (Loreau & Hector 2001; Tilman et al. 2001). These ecological theories concerning the connections between species richness or variety and productivity also apply to the links between stand structural characteristics and aboveground biomass or carbon storage (Poorter et al. 2015). However, in natural forests, stand-structural characteristics as well as species diversity have an impact on the way the forest functions (Poorter et al. 2015; Yuan et al. 2018).

The connections between the structural characteristics of stands and the operational dynamics of forests, encompassing factors like aboveground biomass, carbon storage, and stand productivity, exhibit predominantly positive patterns in sub-tropical forests and agro forests. Conversely, within boreal and temperate forests, the relationships tend to be more varied, involving both positive and negative trends. Experimental plantations or monoclonal stands, on the other hand, often show negative associations or a lack of statistically significant correlations. Interestingly, diverse patterns, encompassing positive, negative, and non-significant links, emerge when considering the interplay between biodiversity indices (encompassing taxonomic, functional, and phylogenetic aspects) and stand structural indices across diverse forest ecosystems. However, there is a prevalent positive correlation between taxonomic diversity indices and stand structural attributes, which contribute to driving forest functioning across global forest ecosystems. Furthermore, a mix of relationships, spanning positive, negative, and non-significant connections, are observed when exploring how environmental factors and other variables relate to stand structural indices in various forest ecosystems. This synthesis underscores the absence of a universal and consistent relationship between stand structure and forest functioning. Instead, this relationship is heavily contingent upon factors such as the specific environmental conditions, interactions among organisms, stand age, and the intensity of disturbances within each unique forest ecosystem (Ali & Yan 2017; Paquette & Messier 2011). Within natural forests, the configuration of stand structure serves as a reflection of various underlying mechanisms, including niche complementarity, regeneration dynamics, competitive interactions, self-thinning processes, and the historical record of disturbances. These structural variations, resulting in features like leaf layering and multilayered canopies, subsequently exert an influence on crucial aspects of forest functioning, such as photosynthesis, respiration rates, and overall stand productivity (Poorter et al. 2015). The documented positive impact of stand structural attributes on forest functioning can be attributed to the augmentation of resource utilization complementarity (Ali & Mattsson 2017).

Each tree species, characterized by a range of tree sizes, holds distinct requirements for water and light within a forest stand. This leads to the notion that a diverse and varied stand structure can yield an amplified effect of niche complementarity. This effect operates by efficiently harnessing and utilizing light, along with other essential resources. Conversely, reduced complexity in stand structure may lead to a weakening of the niche complementarity effect (Ali et al. 2016; Wang et al. 2011). The positive impacts of stand structural attributes on forest functioning can be attributed to the potential for higher canopy density resulting from increased vertical spatial occupation. This, in turn, facilitates enhanced capture and utilization of aboveground light within the stand itself (Yachi & Loreau 2007). Stand structure complexity serves as the pivotal mechanism that underpins the positive connections between species diversity and forest functioning. This mechanism operates by facilitating heightened resource acquisition and utilization, as well as fostering interactions among individual trees or species in boreal and temperate forest ecosystems (Dănescu et al. 2 6; Zhang & Chen 2015). A similar correlation between structure and species diversity is observed in natural tropical forests, where a wider array of tree sizes and increased species richness within each size class result in the development of a multi-layered forest canopy. This intricate canopy structure effectively allows for enhanced filtration of light (Poorter et al. 2015; Van Con et al. 2013). If this correlation extends to plantations, then the promotion of mixed and uneven-aged plantations becomes more advantageous compared to monocultures and even-aged plantations. This is due to the potential of mixed and uneven-aged plantations to more effectively promote aboveground biomass, store carbon aboveground, and bolster stand productivity. The variance in individual tree sizes, which embodies the concept of niche complementarity, stands as the primary underlying mechanism driving forest functioning (Zhang & Chen 2015). However, its significance may vary concerning the maintenance of species diversity within a specific forest ecosystem (Dănescu et al. 2016; Yuan et al. 2018; Zhang & Chen 2015). For instance, initial hypotheses suggested that the inequality in individual tree sizes acts as the bridging mechanism responsible for positive relationships between forest diversity and productivity in natural (boreal) forests (Zhang & Chen 2015), based on the overarching idea that stand structure is pivotal for upholding species diversity.

Nonetheless, recent research has indicated that stand structural attributes - encompassing tree diameter, height diversity, and individual tree size inequality - as well as species diversity, exert direct and independent influences on forest functioning, with stand structure proving to be a more potent predictor (Yuan et al. 2018). This slight discrepancy observed between one empirical study and subsequent investigations might have arisen due to the intricate interplay of various measures of species diversity, as well as the influences of both interspecific and intraspecific variation in trees sizes, all contributing to driving forest functioning (Yuan et al. 2018). In this context, it's worth noting that a recent study discovered that intraspecific tree size variation also holds a significant role in enhancing the functioning of agroforestry systems. Consequently, the study recommended the explicit incorporation of intraspecific tree size variation into the theoretical framework (Ali & Mattsson 2017a). In light of these observations, it's prudent to suggest that further research is required to more comprehensively assess the niche complementarity effect, specifically by focusing on the impact of stand structural attributes in elucidating forest functioning within intricate forest ecosystems.

1.9 Relationships of environmental factors with forest diversity, structure, and functioning

Environmental filtering plays a pivotal role in shaping forest communities through its response to climatic fluctuations at both local and regional scales (Kraft & Ackerly 2010;). Notably, the relationships among species diversity, tree size variation, and aboveground biomass on a regional scale can be significantly impacted by abiotic factors within natural forests (Poorter et al. 2015; Rodrigues et al. 2016). Topography is often regarded as a pivotal driving force governing the spatial variability of crucial factors like precipitation, temperature, and soil fertility. These factors, in turn, hold the potential to shape forest diversity, structure, and overall functioning (Jucker et al. 2018; Pinho et al. 2018; Rodrigues et al. 2019). Although various abiotic elements exert complex influences on species distribution patterns, it is notable that regional-scale forest diversity, structure, and aboveground biomass are predominantly regulated by precipitation and temperature, compared to the more variable impacts of soil fertility (Prado-Junior et al. 2016). While the direct influence of environmental filtering on species richness and composition is recognized (Toledo et al. 2012), the relative and indirect significance of environmental filtering mediated by differently sized competitor trees remains inadequately explored. Additionally, it is anticipated that precipitation and temperature can impact species richness and aboveground biomass either directly or indirectly through moderate, medium, and weak competitor trees or vice versa. However, for the big-trees the energy hypothesis posits that available energy fosters the growth of a few large-diameter trees, consequently forging a connection between forest diversity, structural attributes, and aboveground biomass. Prominent ecological theories on a large scale, supported by empirical studies, indicate that biodiversity and ecosystem functions are predominantly influenced by favorable climatic conditions (Gillman & Wright 2014; Ali et al. 2018). Nonetheless, a variety of local-scale ecological mechanisms have been proposed to elucidate the relationships between biodiversity and ecosystem functioning (Ali et al. 2016; van der Sande et al. 2017).

In natural forest ecosystems, elevated species diversity and aboveground biomass tend to be concentrated in areas with ample precipitation or favorable water availability (Poorter et al. 2015; Liang et al. 2016; Ali et al. 2018). This occurrence might be attributed to niche differentiation and facilitation, which promote the growth of individual trees in the presence of favorable climatic conditions within species-rich tropical forests (Toledo et al. 2012; Poorter et al. 2017). Consequently, biodiversity might substantially enhance aboveground biomass productivity due to facilitation effects, particularly in challenging environmental conditions, in contrast to the competitive effects more prevalent in less productive settings within species-poor forests (Paquette & Messier 2011). Moreover, the soil fertility hypothesis proposes that plants can thrive in environments with high nutrient availability, although this can also intensify competition (Quesada et al. 2012). However, numerous tropical forest species grow in wet but nutrient-poor soils (Swaine 1996), leading to uncertainties about the extent to which nutrient limitation affects natural tropical forests (Prado-Junior et al. 2016). It is well-established that within natural forests, species exhibiting acquisitive and conservative traits tend to inhabit contrasting ends of the soil nutrient spectrum, corresponding to nutrient-rich and nutrient-poor soils, respectively (Fortunel et al. 2014; Ali & Yan 2017). In this context, it is reasonable to consider that within natural tropical forests, species diversity contributes to heightened aboveground biomass and demographic processes like growth and recruitment under favorable climatic conditions rather than in environments characterized by high soil fertility (Toledo et al. 2012; Poorter et al. 2015; Poorter et al. 2017). The concept of multilayered stand structures has been theorized to enhance the capture and utilization of light among and within component species in a community, achieved through niche differentiation and facilitation mechanisms (Yachi & Loreau 2007). Nonetheless, the influence of species diversity on aboveground biomass within a forest stand or community can manifest as both direct increases or decreases. This phenomenon can be attributed to various ecological mechanisms, including niche complementarity, mass ratio effects, selection, competitive exclusion, and more (Szwagrzyk & Gazda 2007; Poorter et al. 2015; Ali et al. 2016; Ali & Yan 2017). Furthermore, it's noteworthy that species diversity and the complexity of stand structure mutually reinforce each other, culminating in the elevation of aboveground biomass or carbon storage through the operation of the niche complementarity effect over time within natural forests (Zhang & Chen 2015; Ali et al. 2016). However, it is also apparent that species diversity and stand structural complexity can serve as direct, independent, or alternative biotic indicators of aboveground biomass, with stand structure demonstrating superior predictive power (Dănescu et al. 2016; Ali & M; Yuan et al. 2018). Consequently, the intricate interrelationships among species diversity, stand structural complexity, and aboveground biomass remain subject to ongoing debate. For instance, the extensively documented direct and indirect impacts of climate and soil conditions on species diversity, stand structural complexity, and aboveground biomass have not frequently undergone explicit testing within complex natural forest environments.

1.10 Forest of Pakistan

The forests in Pakistan serve as a reflection of the country's diverse physiography, climate, and soil conditions. Positioned as an elongated stretch of land extending from the Arabian Sea to the Karakoram mountains, Pakistan spans latitudes 24°N to 37°N and longitudes 61°E to 75°E, covering a total area of 87.98 million hectares. The topography is characterized by expansive mountainous regions in the north, west, and southwest, alongside a fertile plain known as the Indus plain. The northern mountain system encompasses the Karakoram, the majestic Himalayas, and the Hindu-Kush, boasting an impressive collection of snow masses, glaciers, and over 100 peaks exceeding 5400 meters in elevation. K-2, standing at 8563 meters, claims the title of the world's second-highest peak. Due to the steep slopes of these mountains, the associated forest vegetation holds paramount importance from a hydrological standpoint, contributing significantly to the fragility of watersheds. Moving towards the Indus plain, it reveals two distinct landforms: the alluvial plain and sandy deserts. Originating from the snow-covered northern mountain ranges, the Indus river traverses the country, forming a vast delta before finally meeting the Arabian Sea. The Eastern influx of the Jhelum, Chenab, Ravi, and Sutlej rivers into the main Indus river at Panjnad collectively constructs one of the largest irrigation systems globally. Despite the presence of an extensive irrigation system, Pakistan faces a scarcity of forest resources, primarily attributed to the prevailing arid to semi-arid climate across much of the country (refer to Figure 2.1). As outlined in the Forest Sector Master Plan (FSMP) of 1992, a mere 4.8% of the total land area, equivalent to 4.2 million hectares, constitutes natural forest cover. Additionally, 0.117% (103,000 hectares) is designated as irrigated plantations, while a substantial 32.40% (28.507 million hectares) comprises rangelands.

According to FAO (2007) records, the total forest area amounts to 5.01%, equivalent to 4.34 million hectares of which 3.44 million hectares are state-owned, and tree cover on private or farmlands constitutes about 0.887% (0.781 million hectares). The majority of the country forested areas are concentrated in the northern regions, particularly in Khyber Pakhtunkhwa (KPK) and Azad Jammu and Kashmir (AJK), hosting coniferous and scrub forests. Other prominent forest types include *Juniperus*, Chilghoza (*Pinus gerardiana*), scrub, riverine, and mangrove forests. Notably, irrigated plantations, primarily located in Punjab and Sindh provinces, serve as a significant source of timber in the country. Two major environmental factors determining the vegetation types and their dynamics include temperature and precipitation. For instance, if the temperature is below 6°C very few plant species will grow but if the temperature is above 20°C with the availability of the required precipitation amount then the region will have an abundance of plant species. The forest can be a tropical forest forest, subtropical forest, temperate or alpine forest. Most of the forests grow in areas with high rainfall above 1000 mm per annum while grasslands are found in areas with 200 mm to 1000 mm precipitation per year and eventually deserts are found in areas with precipitation less than 200 mm per year. Fortunately, Pakistan holds all such kinds of biomes as compared to other countries of the world with the same area or larger ones. Pakistan has at least 5521 floristic diversity of vascular plants (Gul et al. 2017). It has a total of 372-400 endemic species with 5-monotypic endemic genera i.e., *Douepia*, *Sulaimania*, *Kurramiana*, *Wendelboa,* and *Spiroseris* (Ali 2008).

Pakistan attitudinally comes in a subtropical climatic region of the world but its river systems, valleys, and precipitation patterns make the conditions and vegetation types tropical-like somehow in some places e.g. coastal mangrove forests in Baluchistan and Karachi. High mountain ranges support the alpine, subalpine, and temperate type climates and hence vegetation on the other hand. Pakistan is blessed with various types of forests due to variations in the physiographic, edaphic, and climatic conditions of its different regions. Characteristic forest types of Pakistan are as follows (Rasheed et al., 2017).

1.10.1 Dry Subtropical Thorn Forests

This is the major forest type of Pakistan. This type of forest is widespread across the Indus plains, excluding the driest regions. The vegetation is characterized by short, predominantly xerophytic species, mostly of a leguminous nature with small leaves. The species composition varies from evergreen to deciduous, contingent on geographical location, and thrives in a dry and hot climate. Prominent tree species found in these forests include *Prosopis cineraria*, *Capparis decidua*, *Zizyphus mauritiana*, *Tamarix aphylla*, and *Salvadora oleoides*, alongside numerous shrub species of varying sizes. These forests face a substantial challenge of heavy grazing and browsing, resulting in a stunted tree climax, especially for palatable species. The poor state of trees in these areas is further exacerbated by edaphic and other biotic factors, with increasing salinity, water scarcity, and soil shallowness due to climate change. The average height of trees in these forests ranges from 20 to 30 feet. Before the expansion of agricultural lands, these forests extended from the foothills of the Himalayas and low hills in the southwest Punjab plains and Balochistan to the Arabian Sea. The climax species in these forests are influenced by diverse soil properties, such as soil textures, type, and depth, varying from region to region. As a result, *Salvadora oleoides*, *Capparis decidua*, *Tamarix aphylla*, and *Prosopis cineraria* are prevalent as climax species, adapting to a wide range of soils.

1.10.2 Sub-tropical broad-leaved forest

These forests are distributed across the country, particularly at suitable elevations, including the foot hills of Murree, Margalla hills (Islamabad), Pothowar region, Kalachitta hills (Attock), Salt range (Jehlum), and Suleiman mountain range. Typically situated below the subtropical chir pine forest at elevations ranging from 460 to 920 meters, these forests predominantly align with the foothills and lower slopes of the Himalayas. Characterized by hot, extended summers and brief, cool winters, the climate in these areas features long, dry months. The terrain of these forests is stony and challenging, merging upwards with sub-tropical Chir Pine forests and downwards with Tropical thorn forests. The vegetation is xerophytic, with thorny and small evergreen leaves, mostly broad-leaved. Prominent species include Kao and Phulai, occurring either in mixed or pure forms and the shrub Sanatta, particularly abundant in degraded areas. The estimated total area covered by these forests is 1,108,826 hectares. These forests serve various purposes, including providing small timber, fuelwood, and forage. Scrub forests are suitable for controlled grazing and browsing, and during the monsoon, there is a profuse growth of grasses and herbs, highly conducive to grazing. Alongside the mentioned species, large-dimension *Pistacia* trees are common in moist pockets and higher elevations. The vegetation includes trees like *Acacia modesta*, *Olea ferruginea*, *Zizyphus mauritiana*, *Ticoma undulata*, and shrubs such as Snatha *Dodonaea viscosa*, *Nerium odorum*, *Gymnosporia royleana*, *Carrissa spinarum*, and *Pistacia integerima*. Due to the harsh and unpredictable climate, these forests are primarily managed for soil and water conservation under the Selection wood sylvicultural system.

1.10.3 Moist temperate mixed forest

These evergreen forests consist mainly of conifers, occasionally interspersed with oaks and broad-leaved species. They are situated in Azad Kashmir, Murree, parts of Abbottabad district, Mansehra, Swat, some tribal areas (Hazara and Malakand civil division), and the Naran Kaghan valleys. Elevations range from 1700 to 3350 meters above sea level. These forests transition into dry temperate and, on occasion, sub-Alpine forests. The climate in these regions is characterized by long and cold winters with occurrences of snow and hailstorms. Summers, in contrast, are short, mild, and moist. The mean annual temperatures hover around 12°C, with precipitation ranging from 650 to 1500 mm. The vegetation is defined by a limited number of dominant species, primarily conifers, ensuring a dense canopy cover. Trees in these forests can reach heights between 25 to 50 meters, with stem girths potentially reaching 4.5 meters. Regarded as the most productive forests in the country, deciduous broad-leaved forests can also be found on flat ground with deep soils and in depression areas. However, these areas are subject to activities such as lopping, grazing, and cleaning for cultivation. The diverse flora includes conifers like *Pinus wallichiana*, *Cedrus deodara*, *Picea smithiana*, *Abies pindrow*, *Taxus bacata*, and broad-leaved species such as *Quercus incana*, *Quercus dilatata*, *Quercus semicarpifolia*, *Rhododendron arboreum*, *Aesculus indica*, *Fraxinus hookeri*, *Acer oblongum*. Shrubs in the area include *Indigofera oblongifolia*, *Lonicera japonica*, *Rosa moschata*, *Rubus lasiocarpus*, *Viburnum nervosum*, and *Strobilanthus*. Due to their significant role in the Mangla and Tarbela lake watersheds, special attention is given to soil and water conservation in these forests. They experience heavy monsoon rains during the summers and substantial snowfall in winters, characteristic of these moist temperate zones.

1.10.4 Dry temperate forest

These forests are situated at elevations ranging from 1700 to 3350 meters, covering regions such as Chitral, Nilam valley (AJK), Gilgit, Sakardu, Hunza, Upper parts of Suleiman Mountain Range to the Northwest, including Takht-i-Suleiman, Tribal areas, and district Loralai. Positioned just below the sub-alpine forests, they blend with moist temperate forests towards their lower boundaries. The climate is characterized by long and cold winters, with short, dry summers, featuring a mean annual temperature of less than 500mm and 5 - 15°C, respectively. These forests, beyond the effective reach of Monsoon penetration, exhibit an open canopy with widely scattered trees, resulting in poor productivity and an undergrowth of open scrub. Grazing and browsing, particularly by goats and sheep, are common and intense, disrupting the natural balance of palatable and unpalatable species composition in these forests. Additionally, some shrub species of medicinal and aromatic importance, such as *Artemisia species*, are found in these areas. The main species in these forests include dry zone is *Pinus gerardiana* (Chalghoza), and *Quercus ilex*. Higher up, blue pine communities are present, and in the driest inner tracts, forests of blue pine, *Juniperus macropoda*, and some *Picea smithiana* are locally found. The vegetation comprises

Conifers such as *Cedrus deodara*, *Pinus gerardiana, Pinus wallichiana*, *Picea smithiana*, *Juniperus macropoda*, *Juniperus excelsa*, *Taxus bacata*, Broadleaved such as Juglans regia, *Quercus incana*, *Quercus dilatata*, *Rhododendron arboreum*, *Aesculus indica*, *Fraxinus hookeri*, *Acer oblongum*, *Populus ciliata,* and Shrubs such as *Artemisia maritima*, *Ephedra nebrodensis*, *Prunus padus*, *Lonicera japonica*, *Zizyphus sativa*. The management of these forests follows the Shelters Wood silviculture system.

1.11 Regional knowledge gap: Relationships between forest diversity, structure and functioning across Pakistan

In recent decades the relationships between forest diversity, structure, and function have been one of the major topics in the field of ecosystem functioning research. Nevertheless, a lot of disputes and controversies still exist in this field of research (Hooper et al. 2005). Each forest contains an extremely huge ecosystem from the root to the canopy top and provides a larger biotic surface as compared to other ecosystems. Trees are the explanatory example of forest ecosystem function and they modify their environment because of their absolute size (Nadrowski et al. 2010). In addition, forests link the troposphere with the deep groundwater and regulate climate, improving soil development, initiating nutrients and carbon cycles, and producing organic matter. The relationship between forest diversity, structure, and function might vary in different ecosystems (Steinbeiss et al. 2008). The Variation is not only because of the natural processes and anthropogenic disturbances but also to a large extent because of changes in the environmental conditions, i.e., climatic and edaphic variability‘s. It is important to predict how forests will respond to global environmental change and influence forest functions and services by understanding the effect of various climatic and soil conditions on forest diversity, structure, and function. At small or local scale forest diversity, structure, and function cannot be linked accurately to the determinant factors such as climatic conditions, e.g., temperature and precipitation but can be correlated to topographic and soil conditions more precisely. Topographic factors, such as slope and elevation have been identified as major spatial determinants influencing changes in the forest diversity structure and function at the local scale. Forest diversity, structure, and function might be greatly associated with the climatic conditions and, to a lesser extent, soil-related factors at regional, and continental scales. It is because of the precipitation and temperature factors and their combinations throughout different seasons which become more decisive factors for tree species distribution, structure, and function. That does not mean that soil properties are not of any importance as the physio-chemical nature of soil defines nutrient availability and vegetation of a region (Ali et al. 2020). Will future forests be able to sustain their functions and services? Are we at risk of approaching lower levels of forest functions and services in a world with fewer tree species? These are the central questions of forest diversity structure and function research. This relatively newer discipline in the ecology of forests, began at the start of the 1990s and tries to answer these and many other questions.

Four key hypotheses in forest ecology research describe how forest diversity and structure contribute to ecosystem productivity/functions (Finegan et al. 2015). First, the soil fertility hypothesis (SFH), postulates that an increase in available nutrients increases biomass production when resource availability is higher, and hence the plants can grow faster (Quesada et al. 2012), but it might increase competition, and lead to higher turnover rates and mortality as well (Malhi et al. 2006). Second, the green soup hypothesis (GSH), suggests that vegetation biomass primarily determines productivity and suggests that quantity is more important than the quality of vegetation (Lohbeck et al. 2015). Third is the niche complementarity hypothesis (NCH). According to this within a community, ecosystem function is determined by a variety of functional traits and species that lead to a variety of resource utilization due niche partitioning (Tilman et al. 1997). According to NCH functional traits diversity in an ecosystem, i.e., functional traits divergence (FDvar) of a multivariate trait or single trait should be positively related to aboveground biomass in the natural forests due to ecological niches and complementarity in available resource utilization (Loreau et al. 2001). Fourth, the mass ratio hypothesis (MRH), postulates that within a community abundant plant species functional traits determine ecosystem functions (Grime,1998). Therefore in the natural forest ecosystem, community weighted traits mean (CWM), is greatly determined by aboveground biomass (Prado-Junior et al. 2 6) .

Literature showed that there is no such detailed work on the topic we suggest for our current study under the umbrella of above-mentioned hypotheses for the forests of Pakistan. Nature blessed Pakistan with a diverse type of geography, climate, and forests within an elevation range of 0-8611 meters above sea level. Therefore, a huge research gap and opportunity is found to test the relationship between forest diversity structure and function in a diverse type of climate and soil condition across the country for the first time. In the current research, we are focusing on the relationships between forest diversity, structure, and function in different types, such as dry sub-tropical forests, moist sub-tropical broad-leaved forests, moist-temperate mixed forests, dry temperate coniferous forests, dry temperate pure *Pinus geradiana* forest, in the light of above-mentioned hypotheses. Furthermore, we intend to elaborate on the ecological mechanisms underlying forest diversity, structure, and functions with more depth by using multiple ecological tools and techniques.

1.12 Objectives of the study

- To describe the rrelationship between environment, diversity, and Aboveground Biomass (AGB)
- Relationship between, stand structure diversity, and aboveground biomass in single and multi-species forests
- To clarify the role of big trees in the natural forest ecosystem of Pakistan
- To understand the role of multiple biotic and abiotic drivers of aboveground biomass in the natural forest ecosystem of Pakistan.
- To disentangle the carbon sequestration and its biotic and abiotic determinants in different forest ecosystems of Pakistan

Chapter 2

General methodology

2.1 Study area

Pakistan is located in the northwestern region of South Asia, situated between 24 and 37 degrees north latitudes and 61 and 75 degrees east longitude. It shares its borders with India to the east, Afghanistan to the northwest, and Iran to the west. The southern boundary is defined by the Arabian Sea. The country geography is characterized by a diverse landscape, featuring rocky plateaus within the Indus basin and mountain ranges to the north, which encompass picturesque valleys and snow-capped peaks. A distinctive sequence of three mountain ranges Karakoram, Hindu Kush, and Himalayas covers approximately 60% of the northern expanse of Pakistan. The Karakoram Range extends into Pakistan, while the Hindu Kush stretches across Pakistan, Afghanistan, India, and China. The Himalayas, on the other hand, reach across Asia . There are two other very famous mountain ranges: the Suliman mountain range which is present in the Baluchistan province and the Kirthar mountain range present in the Sindh province of Pakistan. The Himalayas extend within the country, giving rise to Himalayan forests characterized by a dynamic mix of trees, mainly dominated by *coniferus*. Positioned between the sub-alpine and dry temperate zones along the Himalayan range, these forests are found in regions such as Lower Dir, Upper Dir, Swat, Muree-Hazara hills, Kaghan Valley, the upper reaches of Kurram Agency, moist areas in upper Swat, and Gilgit Baltistan. As described by Gupta and Thomas in 2008, these forested areas receive a substantial annual rainfall ranging from 650 mm to 1500 mm. The rainy season typically commences in the summer, usually from July to September, influenced by the southwestern monsoon winds. Winter snowfall contributes to precipitation as well, with the gradual melting of snow in early summer extending the period of sufficient moisture availability. During the winter months from December to February, the average maximum temperature ranges from minus 4.2–1 ° . In contrast, summer in these forests brings humidity levels of up to 57%, occasionally reaching as high as 60% to 70%. The summer temperature averages around 30.1° . The Himalayas are recognized as one of the twenty-five global biodiversity hotspots . On the Pakistani side, the Himalayan moist temperate forests exhibit a higher level of diversity among plants, animals, and fungi. Within these forests, there are gymnosperm-dominated areas featuring species like *Pinus wallichiana*, *Cedrus deodara*, *Abies pindrow*, and *Taxus wallichiana*. Additionally, these forests encompass mixed patches of broad-leaved trees and conifers. In these mixed temperate forests, various species of *Quercus*, such as *Quercus incana, dilatata*, and *Q.*

semicarpifolia along with *Acer acuminatum*, are commonly found. Among the shrub species, *Rosa brunonii*, *Rubus fruiticosus* as well as *Indigofera hebepetala*, *Viburnum cotinifolium* and *Urtica dioica* are prevalent.

2.1.1 Sub-tropical thorn forest

Kirthar National Park is situated in the Kirthar Range in the southwestern region of Sindh, approximately 80 kilometers to the north of Karachi (located between coordinates 27.9014° N to 28.9860° N latitude to 74.9805° E to 75.0234° E longitude). This park holds the designation of being a protected Category II area, as recognized by the International Union for Conservation of Nature (IUCN). Established back in 1974, it is under the jurisdiction of the Sindh Wildlife Department (SWD). Notable characteristics of the park include its rugged terrain and the presence of rare and endangered native large mammals, with a particular highlight being the Sindh Ibex (*Capra aegagrus*).The park's boundaries are delineated by the Mahal Kohistan Wildlife Sanctuary to the south, the Sumbak Game Reserve to the east, and the provincial border with Balochistan to the west.

2.1.2 Topography

The park landscape is defined by relatively low and rocky mountain ranges that run from north to south. These mountain ranges are interspersed with wide, flat valleys, and the elevations within the park vary from 50-1004 meters above sea level. The geological composition of the park is primarily composed of a mixture of sandstones, shales, and limestones. The park's drainage is facilitated by two intermittent rivers: the Baran Nadi, which is a tributary of the Indus River, and the Hab river, which flows in a south-to-westward direction and eventually empties into the Gulf of Arabia.

Figure 1 Topography of the sub-tropical thorn forest.

2.1.3 Soil Condition

In the lowland plains, the soil is characterized by being sandy, loose, and containing a minimal amount of solid material, with little to no soil depth. However, in the mountains, the soil is shallow or even absent altogether. In some areas near perennial springs, there can be localized high salinity levels. The primary source of water for sustaining perennial woody vegetation and human use comes from groundwater aquifers. The depth of the water table can vary significantly, ranging from just a few meters to over 100 meters.

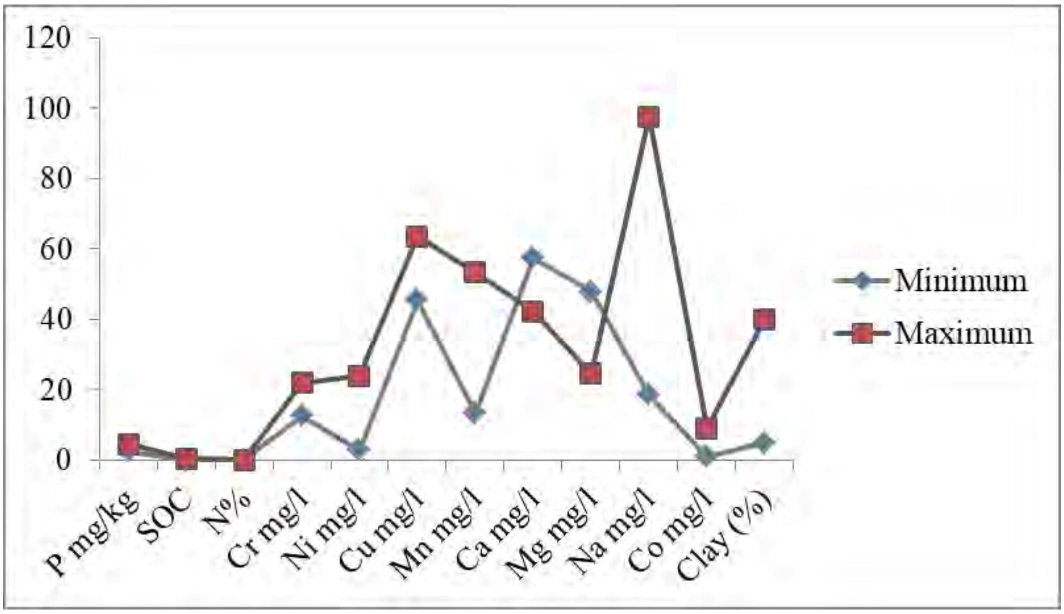


Figure 2 Soil physicochemical properties of sub-tropical thorn forest.

P= Soil Phosphorus, SOC= Soil Organic Carbon, N= Nitrogen, Cr= Chromium, Ni= Nickel, Cu= Copper, Mn= Manganese, Co= Cobalt, Mg= Magnesium, Ca= Calcium, Na= Sodium, Clay loam= Soil Clay loam particals, mg= milligram, kg= Kilogram, l= Litter, %= Persentage.

2.1.4 Climatic condition

Within the park boundaries, there are no dedicated climate monitoring stations. However, data from nearby stations, such as Hyderabad, Karachi Airport, and Manora, provide insight into the climate. These stations have reported mean annual rainfall figures ranging from 186– 214 mm, collected over periods spanning from 52–116 years (with median rainfall values falling between 140– 163 mm). It is important to note that the annual rainfall in the region exhibits high unpredictability, with a coefficient of variation ranging from 76% to 82%. The majority of rainfall occurs during the summer monsoon season, typically between June and September. As for temperatures, the mean monthly temperature at Hyderabad varies from 18.2°C in January to 33.6°C in May. Moving towards the northwest, rainfall decreases while the temperature range widens. Short-term climate data from Dureji, Balochistan, provides additional insights, indicating a mean annual rainfall of 65 mm. The mean monthly temperature in Dureji ranges from 15°C to 38°C, and estimated evapotranspiration stands at 2240 mm .

2.1.5 Vegetation

In the five-year period from 1996 to 2000, which preceded the vegetation survey discussed here, the Kirthar National Park experienced drought conditions. During these years, the annual rainfall in Hyderabad was less than half of the average annual rainfall. The park is primarily characterized by open communities of small trees and shrubs, with some of these being deciduous during the winter or dry season. Among the common species found in the park are *Prosopis cineraria*, *Tamarix aphylla*, *Lycium shawii*, *Salvadora oleoides*, and *Zizyphus nummularia* (Enright et al., 2005). Typically, the vegetation cover in the park remains low, rarely exceeding 20% during the dry season. However, following the summer monsoon, there is a temporary surge in vegetation cover as ephemeral grasses and herbs emerge from a dormant soil seed bank. This temporary increase in vegetation provides grazing and browsing opportunities for wildlife and livestock. Human activities within the park primarily revolve around agricultural production, including crops such as *Gossypium arboretum, Allium cepa,* and *Triticum aestivum* in irrigated fields, as well as *Vigna radiata*, and *Vicia lens*. Livestock grazing, primarily *Capra hircus* , is also a common practice. The population of both people and livestock in the park varies with the seasons and is influenced by the yearly monsoon rains. During periods of increased rainfall, the population could swell by up to 30%, leading to the establishment of approximately 4,100 temporary villages within the park.

Figure 3 Vegetation of the sub-tropical thorn forest.

2.2 Sub-tropical broad-leaved forest

The Sub-tropical broad-leaved forest within the Margalla Hills National Park (MHNP) was designated as a National Park through the Islamabad Wild Life Ordinance in 1980. This decision was made to safeguard natural resources from unsustainable human activities, including practices such as over-cultivation, grazing, mining, and water pollution. MHNP is situated in the lower Himalayas, with geographic coordinates spanning approximately 33°43'N and 72°55'E. It encompasses an area of around 17,386 hectares, with elevations ranging from 450–1580 meters above sea level. The park's topography is characterized by irregular terrain featuring gullies and steep slopes, and its predominant rock composition is limestone (Masud et al. 2023).

2.2.1 Topography

The region's topography is characterized as rugged, with varying elevations primarily consisting of steep slopes and gullies, where the predominant rock composition is limestone.

2.2.2 Soil conditions

The soil in the research area is a product of wind and water-driven deposits, as well as sedimentary rocks. It varies in color from dark brown to yellowish-brown and has a fine texture. The Margalla Hills primarily date back to the Tertiary period, although there are smaller sections composed of quartzitic sandstone, calcareous shale, and limestone formations.

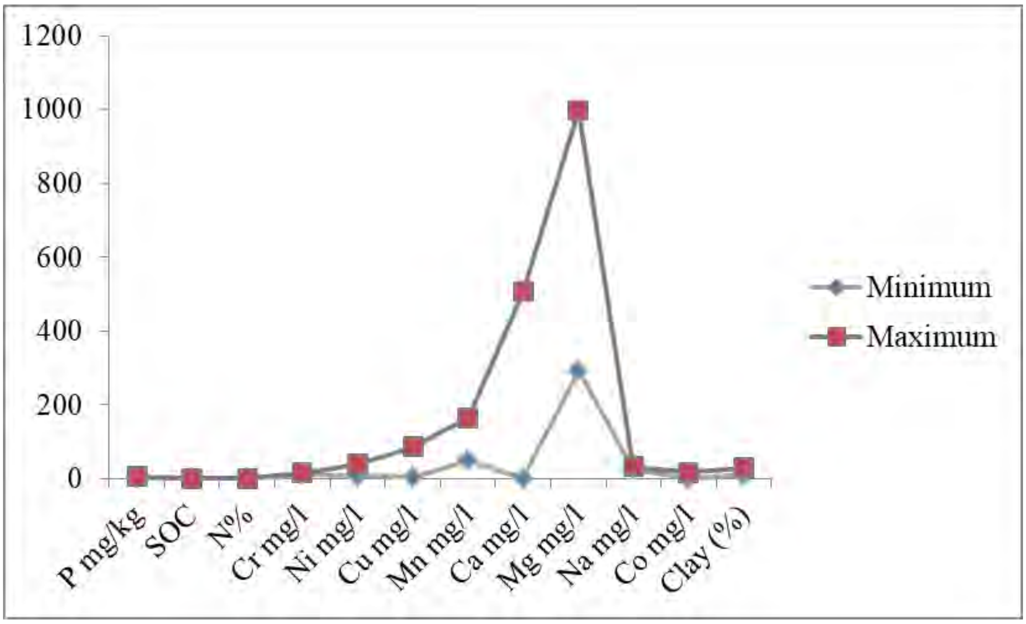


Figure 4 Soil physicochemical properties of sub-tropical broad-leaved forest.

P= Soil phosphorus, SOC= Soil organic carbon, N= Nitrogen, Cr= Chromium, Ni= Nickel, Cu= Copper, Mn= Manganese, Co= Cobalt, Mg= Magnesium, Ca= Calcium, Na= Sodium, Clay loam= Soil clay loam particals, mg= milligram, kg= Kilogram, l= Litter, %= Persentage.

2.2.3 Climatic conditions

The climate within Margalla Hills National Park can be classified as sub-tropical to semi-arid. The typical range for average temperatures spans from a maximum of 34.3°C to a minimum of 3.4°C, while the average annual precipitation amounts to approximately 1200 mm per year.

2.2.4 Vegetation

In Margalla Hills National Park, *Dodonaea viscosa* stands out as the most prevalent shrub species. An analysis conducted by Akbar in 1988 identified seven distinct vegetation communities within the Quaid-i-Azam University campus. Furthermore, they observed the presence of a *Pinus roxburgii* and *Quercus incana* community on the north-facing slopes, while the south-facing slopes featured an *Acacia modesta*, *Woodfordia fruticosa*, *Dodonaea* community. According to their findings, the north-facing slopes exhibited higher species diversity compared to the south-facing slopes, with a similarity index of 46%.

Figure 5 Vegetation and topography of the sub-tropical broad-leaved forest.

2.3 Moist temperate mixed forest

The Moist temperate mixed forest located in Muree and Ayubia is a part of the Himalayas, recognized as one of the world's ecological hotspots due to its remarkable biodiversity and ecological importance. This particular forested area, nestled within the western Himalayas of Pakistan, holds significant fame as a popular hill station and a renowned tourist destination. Geographically, the Moist temperate mixed forest spans from approximately 33.9281 to 34.2303 degrees North Latitude and 73.3844 to 73.6678 degrees East Longitude. It covers an elevation range from 1041–2566 meters above sea level.

2.3.1 Topography

The topographical features of these forested areas are marked by towering mountains, steep slopes, and nestled inner valleys. In geological terms, these mountains were formed as a result of the collision between the Indian and Eurasian tectonic plates, with a subsequent rapid rise during the early Eocene period, which occurred approximately between 47.8–56 million years ago (Khan et al., 2016). The elevation within these forests spans from 1041–2566 meters above sea level.

2.3.2 Soil condition

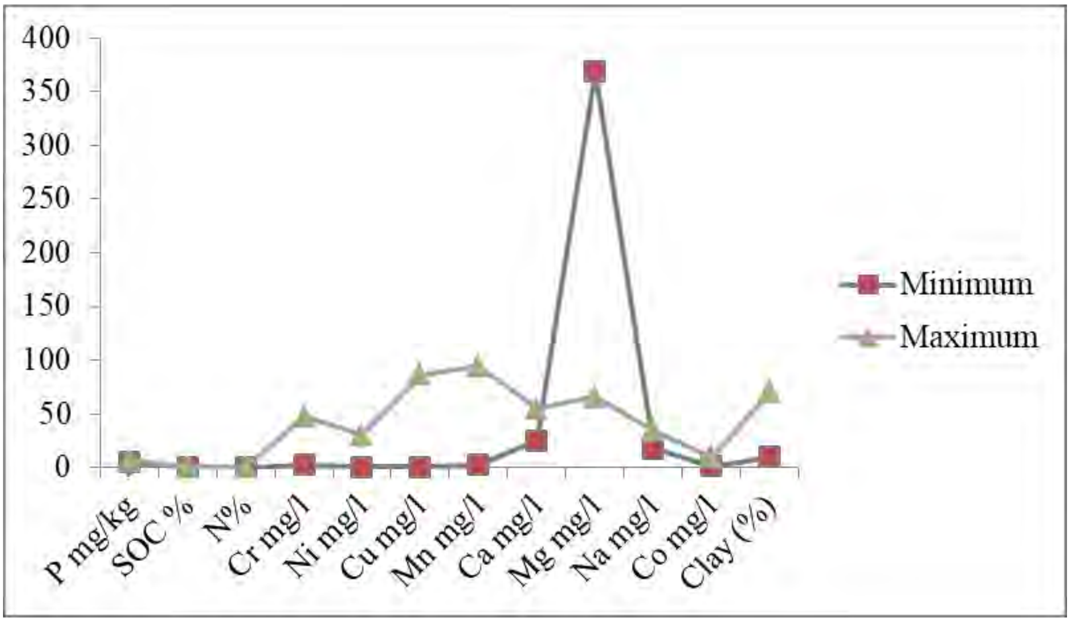


Figure 6 Soil physicochemical properties of moist temperate mixed forest.

P= Soil phosphorus, SOC= Soil organic carbon, N= Nitrogen, Cr= Chromium, Ni= Nickel, Cu= Copper, Mn= Manganese, Co= Cobalt, Mg= Magnesium, Ca= Calcium, Na= Sodium, Clay loam= Soil Clay loam particles, mg= milligram, kg= Kilogram, l= Litter, %= Percentage.

2.3.3 Vegetation

The area is important as it hosts *Cedrus* and chir pine forests. These forests are dominated by mixed types of vegetation. *Pinus wallichiana*, *Cedrus deodara*, *Abies pindrow*, *Aesculus indica*, *Castanea dentate*, *Diospyros virginiana*, *Quercus dilatata*, *Pyrus pseudopashia*, and *Pyrus calleryana*.

Figure 7 Vegetation and topography of the moist temperate mixed forest.

2.4 Dry temperate conifer forest

The dry temperate conifer forest is situated within Kumrat valley in Dir upper, Khyber Pakhtunkhwa (KPK), positioned to the northwest of KPK and north of Dir proper (Dir Upper). The geographic coordinates for this area are approximately 35°32' .44″ N latitude and 72° 3' 45. ″ E longitude. Kumrat Valley serves as an alluring destination for travelers, drawing people from across the country, especially during the summer, to enjoy its lush vegetation, the meandering Panjkora river, snow-covered landscapes, dense forests, and cloud-kissed hills. This captivating scenery not only pleasures visitors but also contributes to the region's environmental richness, fostering a diverse range of flora and fauna. Kumrat is nestled in the foothills of the Hindukash mountain range, bordered by Chitral to the north, Kalam Swat valley to the east, Ayun valley Chitral to the west, and Lower Dir to the south.

2.4.1 Topography

The elevation of the area ranges from 2,439–3,048 m. Major types of rocks in the study area are granite, diorite, norites, and schist.

2.4.2 Soil conditions

The soil is mostly loam or sandy loam. The soil pH is 5.83–6.22. The mean soil bulk density is . 3 g m·cm⁻ . The soil organic matter ranges from 3.12% to 4.77%.

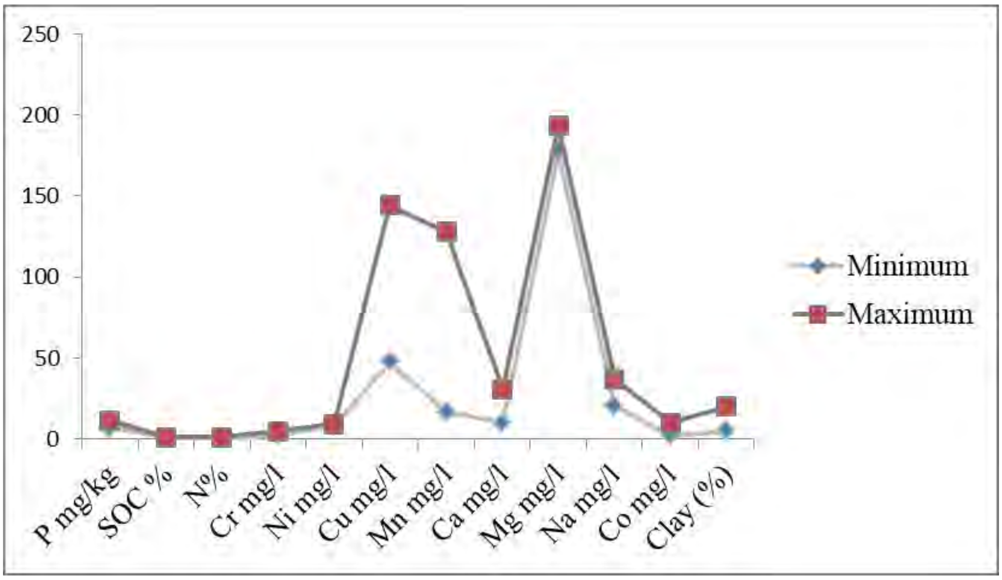


Figure 8 Soil physicochemical properties of dry temperate conifer forest.

P= Soil phosphorus, SOC= Soil organic carbon, N= Nitrogen, Cr= Chromium, Ni= Nickel, Cu= Copper, Mn= Manganese, Co= Cobalt, Mg= Magnesium, Ca= Calcium, Na= Sodium, Clay loam= Soil Clay loam particles, mg= milligram, kg= Kilogram, l= Litter, %= Percentage.

2.4.3 Climatic conditions

In the dry temperate coniferous forest, the climate exhibits alpine characteristics. Summers are notably chilly, with average temperatures ranging from 20°C to 25°C. However, due to heavy snowfall in the winter season, typically between 3 and 11 feet,, temperatures plummet to very low levels with observed temperatures in the range of -4°C to -10°C. Throughout the year, temperature variations span from 0.10°C to 25°C, indicating a significant range of thermal conditions. Monthly mean minimum and maximum temperatures have been documented at 11.22°C and -2.39°C, respectively. Regarding precipitation, the maximum recorded rainfall in this area reaches up to 225 mm, while the minimum stands at 100 mm. On average, the annual rainfall falls within the range of 800– 1200 mm .

2.4.4 Vegetation

The area is dominated by coniferous forest. The major species of the area are *Cedrus deodara*, *Pinus wallichiana*, *Abies pindrow*, *Picea smithiana,* and *Taxus bacata*. *Cedrus deodara* is found in the area as a single dominant species or forms an association with *P. wallichiana*, *A. pindrow*, and *P. smithiana*. In these forests, old age trees are dominant reaching above 50 meters in height same where its height reaches to above 100 meter.

Figure 9 Vegetation and topography of the dry temperate conifer forest.

2.5 Dry temperate pure *Quercus* (Oak) forest

Dry temperate pure *Quercus* forest located at Sheringal valley. Sheringal valley is situated in the northeastern district Dir Upper, about 36 km from the main grand trunk (GT) road of Dir-Chitral. The total area of Sheringal valley is about 870 km^2. The area lies between 35.1967-35.6639 N latitude to 72.0911- 72.3019 N longitude.

2.5.1 Topography

Temperature ranges from .7˚ to 32˚ . The mean annual rainfall varied between 7 mm to 3 mm.

2.5.2 Soil conditions

Dry temperate pure *Quercus* forest has poor soil conditions due to steep slopes. Soil mostly consists of sand and silt. The content of clay loam particle in the soil is very low and this may be the main characteristic of these forests.

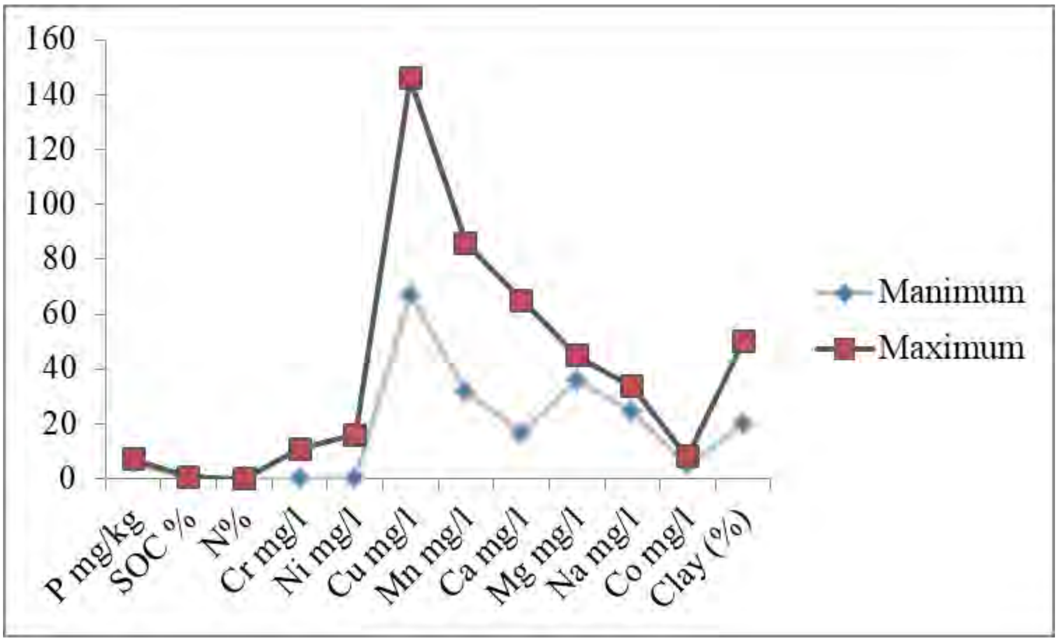


Figure 10 Soil physicochemical properties of dry temperate pure *Quercus* (Oak) forest.

P= Soil phosphorus, SOC= Soil organic carbon, N= Nitrogen, Cr= Chromium, Ni= Nickel, Cu= Copper, Mn= Manganese, Co= Cobalt, Mg= Magnesium, Ca= Calcium, Na= Sodium, Clay loam= Soil Clay loam particles, mg= milligram, kg= Kilogram, l= Litter, %= Percentage.

2.5.3 Climatic conditions

The climate within the dry temperate pure *Quercus* forest exhibits a range from dry to humid, characterized by moderately to severely cold temperatures during the winter months. Between December and February, heavy snowfall is common, leading to a significant temperature drop, with readings plunging as low as -4°C. In contrast, the period from June to September sees much warmer temperatures, typically ranging from 25°C to 35°C. The annual rainfall in this region has been recorded at approximately 1468.8 mm, according to data from the Pakistan Meteorological Department (PMD).

2.5.4 Vegetation

Different plant species are present in the area. In the present study, we only select areas where pure *Quercus* (Oak) forests are present. Generally, *Olea ferruginea*. are also present.

Figure 11 Vegetation of the dry temperate pure *Quercus* (Oak) forest.

2.6 Dry temperate pure *Pinus grerardiana* (Chalghoza) forest

The dry temperate, pure pine forest situated within the Suleiman range, specifically in District Shirani, encompasses an expansive area of 260 square kilometers. Remarkably, it hosts the world's largest *Pinus gerardiana* forest. The Suleiman range itself extends across latitudes ranging from 31° to 36° North and longitudes from 69° to 59° East. The elevation within this range spans from 500–3441 meters above sea level (Khan 2015). The Suleiman Range serves as an extension of the Hindu Kush mountain range and is situated at the confluence of the borders of three provinces: Baluchistan, Khyber Pakhtunkhwa, and Punjab. *Pinus gerardiana*, a highly significant tree species both ecologically and economically, thrives in these forests. These forests are particularly well-suited to dry temperate regions and are known to prefer rocky microhabitats. The Chilgoza pine forests, consisting of natural and pure stands of *Pinus gerardiana*, are predominantly concentrated within the Koh-e-Sulaiman mountain range in Pakistan. According to the assessments these natural, untarnished stands of Chilgoza pine forests span an approximate geographic area 200–260 square kilometers.

Figure 12 Vegetation of the dry temperate pure *Pinus grerardiana* (Chalghoza) forest.

2.6.1 Topography

The Suleiman Mountain Range, renowned for hosting the highest peak referred to as the Solomon Throne (Takht-I-Sulaiman), serves as a natural extension of the Hindu Kush. The arid ecological characteristics of this region, combined with its rugged mountainous terrain, create highly favorable climatic conditions for the flourishing Chilgoza forests. The Suleiman Range is characterized by steep slopes, and these slopes vary in their orientation towards different solar aspects, including north, south, east, and west-facing slopes.

Figure 13 Showing topography of the sub-tropical thorn forest.

2.6.2 Soil conditions

Suleiman Mountain Range has poor soil conditions due to steep slopes. Soil mostly consists of sand and silt. The concentration of clay loam particle in the soil is very low and this may be the main characteristic of this forest.

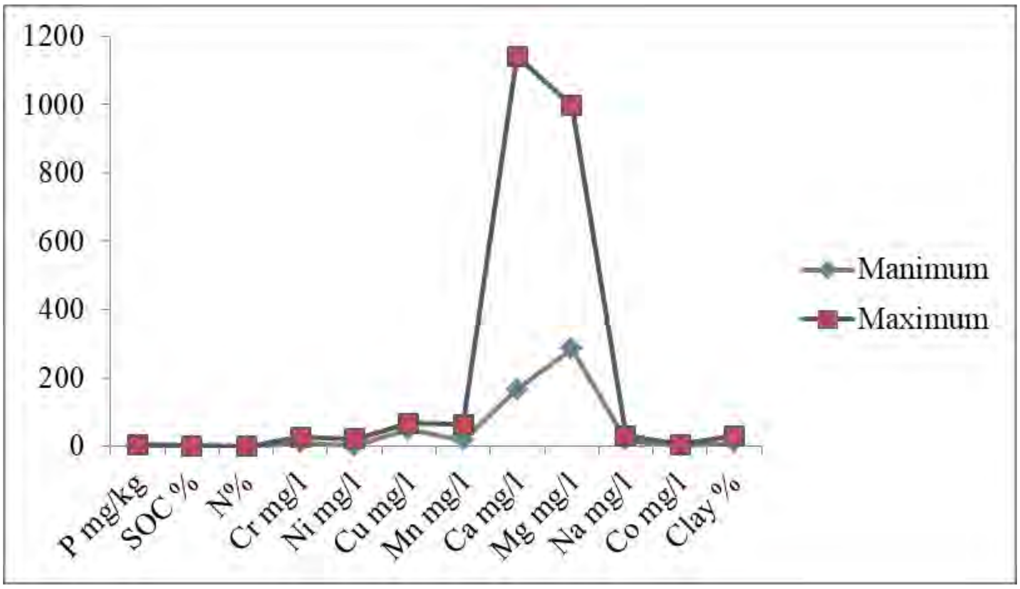


Figure 14 Soil physicochemical properties of dry temperate pure *Pinus grerardiana* (Chalghoza) forest.

P= Soil phosphorus, SOC= Soil organic carbon, N= Nitrogen, Cr= Chromium, Ni= Nickel, Cu= Copper, Mn= Manganese, Co= Cobalt, Mg= Magnesium, Ca= Calcium, Na= Sodium, Clay loam= Soil Clay loam particles, mg= milligram, kg= Kilogram, l= Litter, %= Percentage.

2.6.3 Climatic conditions

The average daytime temperatures in this region typically range from approximately 37°C in June to around 13°C in January. Rainfall is relatively sparse, measuring approximately 320 mm annually, and it tends to vary with altitude. Rainfall is more prevalent during the winter season (WWF-Pakistan 2014).

2.6.4 Economic value

Pinus gerardiana nuts hold greater economic value compared to timber, and they represent the primary marketable product within the Suleiman Mountain Range (SMR) region. In the year 2017, Pakistan achieved a Chilgoza nut production of 3500 metric tons, surpassing the previous year's output. Presently, the market price for Chilgoza nuts in Pakistan stands at 3850 rupees per kilogram. Pakistan's Chilgoza nut production accounts for 18% of the global total. Chilgoza nuts follow a natural cycle that results in a good crop yield every alternate year. The pricing of Chilgoza nuts is subject to fluctuations due to market supply and demand dynamics. Consequently, Chilgoza cultivation presents an income source with inherent instability for local communities. In recent years, there has been a significant surge in Chilgoza nut prices, contributing to an overall increase in the income of the local community. Chilgoza nuts are harvested both by forest landowners and contract harvesters in this region. Some harvesters may not possess land within the Chilgoza forest area, so they enter into contracts with landowners before the harvesting season. In these contracts, the landowner typically receives 50% of the profits from the sale of Chilgoza nuts in the market. However, it is the contractor who manages and covers the labor costs associated with the Chilgoza harvesting during the season. Once the Chilgoza nuts are harvested, they are transported to the local village. In Zhob, wholesalers take charge of the transportation costs from the village to Zhob city. From Zhob, the raw Chilgoza nuts are further transported using smaller vehicles to Dera Ismail Khan. Subsequently, these nuts are loaded onto larger vehicles for transportation to a wholesaler based in Akbari Mandi, Lahore. Akbari Mandi in Lahore serves as Pakistan's largest dry fruit market, where Chilgoza nuts and other nuts are distributed to local markets in various cities and are also exported to international markets. The overall transportation costs from Zhob to Lahore are borne by the wholesale dealers in the Chilgoza trade network. The pricing of Chilgoza nuts is determined in Lahore, where it is influenced by the prevailing dynamics of demand and supply. In Pakistan, Chilgoza nuts hold significant value for wholesalers, and these wholesalers are responsible for supplying roasted or raw nuts to retailers in Lahore. Retailers, in turn, purchase these nuts from wholesalers and sell them to consumers in various urban cities, factoring in their retail margin. Dubai stands out as the largest global exporter of Chilgoza nuts, boasting the world's largest dry fruit market. Each Chilgoza tree can yield an average 12-foot log with a 1.5-foot diameter. Using this calculation, the estimated total volume of logs would be around 17.7 cubic feet. Assuming a 60% loss during processing, the net volume of usable timber comes to 7.1 cubic feet. When comparing the revenue generated from selling Chilgoza nuts with that from timber sales, it becomes evident that Chilgoza nut sales generate higher revenue .

Figure 15 Vegetation of the dry temperate pure *Pinus grerardiana* (Chalghoza) forest

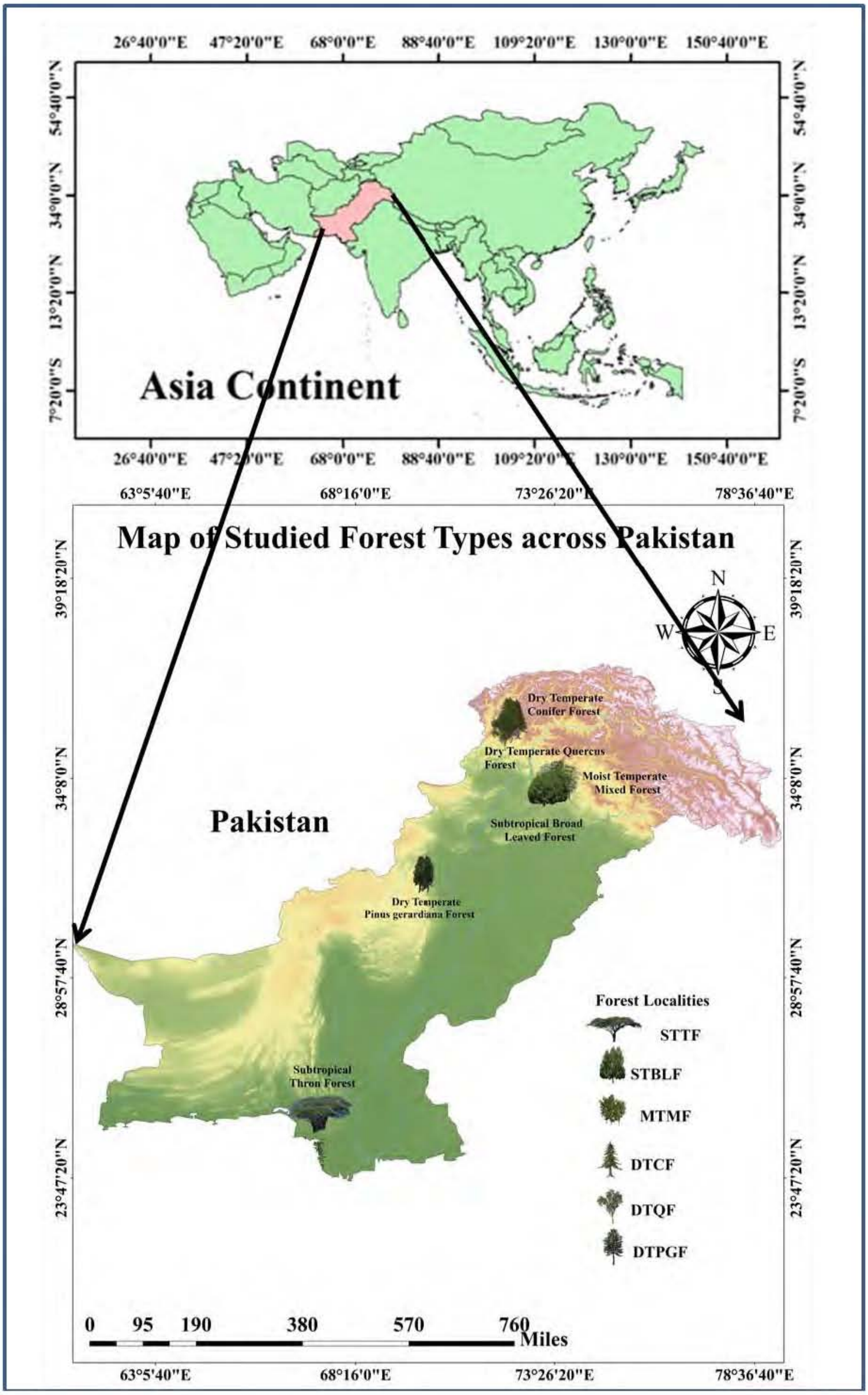


Figure 16 map of the the study forest sites

2.7 Forest inventory

We selected 200 (20 × 20 m) plots from six different forest types (40 plots each forest) From March to September 2020. Each plot was set up at a distance of one kilometer or a 20-meter difference in elevation. ll the plants present in the plot having DBH ≥ cm were identified by a taxonomist and confirmed at (http://www.theplantlist.org/tpl1.1/search at http://www.efloras.org/flora_page.aspx?flora_id=5). The number of individuals per species was noted for the calculation of the Shannon diversity (SD) index and species richness (SR). Tree diameter at breast height (DBH) and crown area were recorded using a measuring tape, similarly, tree height was also calculated for every individual present in the plot using a clinometer. Diameter at breast height, height, and crown area was considered as the stand structure diversity (SSD) of the forest, and Shannon diversity was used as species diversity (Danescu et al. 2016). Within each plot, we cut 10 cm of wood with a diameter of up to 0.5 cm from fresh and exposed branches that were also collected from three individuals of every species to find out the species-specific wood density. Measurement of plant traits, i.e., mean leaf area, specific leaf area, leaf dry matter content, leaf thickness, and wood density were measured from three healthy individuals of every species in each plot. Here, we selected healthy individual trees per species by following the standard protocols: (1) without leaf damage, (2) no oozing sap flow, and (3) no wilting or dieback. For leaf trait measurements, three branches were cut from three different positions (upper, mid, and lower) of the sunlit side of the tree crown, and then twenty to thirty mature leaves were harvested from each branch. In some cases such as in *Pinus* and *Acacia* species maximum number of leaves was collected for better results. Soil samples were collected from 1–10 cm in depth from every plot and kept in polythene bags for further analysis. Geographical coordinates were noted using geographical positing systems for climatic data extraction.

2.7.1 Determination of wood density (WD)

Wood density is the measure of dry mass in moist wood of plant species. The wood density of respective plant species was determined using a 10cm long wood sample taken from a branch. The bark of each moist wood sample was removed and its volume was measured through water displacement in a graduated cylinder. Then, the wood samples were dried promptly and their dry mass was noted using the digital balance. Further, their density (g/cm3) was measured by dividing their dry masses (g) by respective volumes (cm3) (Equation 1). The total wood density of each plot was calculated by summing up the wood densities of all plant species existing in them. Finally, the mean wood density (MWD) of each plot was determined by dividing the total density of individual plots by the number of plant species present in them.

Equation 1

$$WD(g/cm^3) = \frac{Wood\ dry\ weiht}{Volume\ of\ wood}$$

2.7.2 Determination of leaf traits

2.7.2.1 Leaf area (LA)

The leaves were placed on white paper along with a scale. Pictures were taken after adjusting. These pictures were then analyzed with Image J software to determine the total leaf area.

2.7.2.2 Specific leaf Area (SLA)

Specific leaf area was determined by using the following formula

Equation 2

$$\text{SLA} = \frac{Leaf\ Area}{Leaf\ Dry\ weight}$$

2.7.2.3 Leaf dry matter content (LDMC)

Leaf dry matter content was found with the help of below mentioned formula

Equation 3

$$\text{MVD} = \frac{Leaf\ Dry\ weight}{Leaf\ Fresh\ weight}$$

2.7.2.4 Leaf thickness (LT)

Leaf thickness for every individual leaf was measured using a digital vernier caliper

2.7.3 Determination of aboveground biomass

2.7.3.1 Temperate forests

Various methods are used to estimate the above-ground biomass of plant species in different temperate forest types. In current research work the aboveground biomass of plant species was assessed through a non-destructive method using a standard protocol (Chave et al. 2014).

For aboveground biomass determination, the following equations were used.

Equation 4

$$\text{AGB} = 0.0673 \times (\text{WD} \times \text{DBH}^2 \times \text{H})^{0.976}$$

Where (0.673) is the Standard value for temperate forests, (WD) represents the wood density (g/cm3), DBH represents diameter at breast height, (H) represents plant height, and (0.976) is the standard power value.

2.7.3.2 Broad-leaved forest

In the broad-leaved forest, we used the following equation for the determination of aboveground biomass (AGB).

Crown biomass

Equation 5

$$Wc = 0.0980\ (D)^{1.6481} \times (L)^{0.4610}$$

Where *Wc* is the weight of the crown (0.8980) is the standard value of broad-leaved forest *D* is the diameter breast height (1.6481) is the standard power value, *L* is the length of the crown, and (0.4610) is the standard power value.

Stem biomass

Equation 6

$$W_S = 0.0560\ (D)^{0.8099} \times (H)^{1.8140}$$

Where *Ws* is the weight of the stem (0.0560) is the standard value of a broad-leaved forest *D* is the diameter breast height (0.8099) is the standard power value, *H* is the height of the plant, and (1.8140) is the standard power value.

$$\text{Aboveground biomass (AGB)} = Wc + W_S$$

2.7.4 Determination of Shannon diversity index

The given equation was employed to calculate Shannon diversity.

Equation 7

$$\text{Shannon Index} = \sum Pi \ln Pi\ s\ i=1$$

Where Pi is the important proportion, interpretation is made simpler when heterogeneity is expressed in terms of the antilogarithm of *H'*. The number of equally common species that would yield the same heterogeneity, or H', as the sample is measured by Exp (*H'*).

2.8 Soil analysis

The collected soil was further processed for physicochemical properties which are the following.

2.8.1 Soil clay loam

Soil clay loam properties were determined through sieve methods at the plant ecology and conservation laboratory at Quaid-i- z am University Islamabad, Pakistan.

2.8.2 Soil carbon nitrogen phosphorous (CNP)

For the determination of soil carbon nitrogen phosphorous (CNP), samples were sent to Punjab gr iculture Research enter in Rawalpindi, Pakistan.

2.8.3 Soil macro and microelement

First, soil samples were dried and crushed. Stones and pebbles were removed. The 1 g of soil was taken into a flask and mixed with 10 mL of solution prepared by 75% HNO_3 and 25% H l O4. The Prepared samples were then digested on a hot plate until the color changed. Samples were then left to cool down and 40mL of distilled water was added afterwards. Samples were then filtered with the help of filter papers and were kept in plastic bottles for further tests through atomic absorption spectrometry (AAS). All samples were then analyzed through AAS to check the concentration of macronutrients chromium (r) , nickel (Ni), copper (u), manganese (Mn), and micronutrients such as cobalt (o), Magnesium (Mg), calcium (a), and Sodium (Na) (h mad et al. 2 9) .

Table 1 Variable description

S. No.	Variables	Full form	Description
	G E	bove ground Biomass	G B= . 673 × (WD × DBH²× H) .976
2	SSD	Stand Structure Diversity	i. Diameter at Breast Height (DBH) ii. Height iii. rown r ea
3	SD	Shannon Diversity Index	Shannon Index= $\sum_{i=1}^{s} Pi \ln Pi$
4	WM	ommunity Weighted Traits Mean	WM of SL , LT, ML , LDM , and WD
5	BT	Big Trees	DBH (greater than 5 cm)
6	lay loam	Soil lay loam Particles	Determined through Sieve methods

7	NP	Soil arbon, Nitrogen and Phosphorus	Punjab g riculture Research enter Rawalpindi, Pakistan
8	SMP	Soil macro Properties	obalt (o), Magnesium (Mg), alcium (a), nd Sodi um (Na). Through tomi c absorption spectrometry. t the Department of Biochemistry Quaid I z am University Islamabad, Pakistan.
9	SmP	Soil micro Properties	hromium (r) , Nickel (Ni), opper (u), Manganese (Mn).
	MP	limatic Factors	Mean Precipitation, Obtained from Pakistan Metrological Department, Islamabad, Pakistan
	Mt	limatic Factors	Mean temperature, Obtained from Pakistan Metrological Department, Islamabad, Pakistan
2	MRH	limatic Factors	Mean relative Humidity and wind pressure Obtained from Pakistan Metrological Department, Islamabad, Pakistan
3	MWP	limatic Factors	Mean wind pressure, Obtained from Pakistan Metrological Department, Islamabad, Pakistan

2.9 Statistical Analysis

To investigate the impact of climate, soil, big trees, medium trees, small trees, and SD on aboveground biomass, a structural equation model (SEM) was developed. The goodness of fit (GFI) was assessed using several statistical tests, such as the Chi-squared test, comparative fit index (CFI), standardized root mean square residual (SRMR), Bayesian information criterion (BIC), and Akaike's information criteria (AIC). To determine whether the data were multi-collinear, a variance inflation factor (VIF) test was performed. The VIF test has roughly 2.50 relevance in our case. Linear regression was employed to determine the complete path measurements of the structural equation modeling (SEM) results for each conceptual path (Figure 1). Scatter plots were used by employing the function plot (x, y) to investigate the relationship between aboveground biomass and structural diversity. The linear models between y and x were fitted using the function lm (). All the analyses were done in R 3.6.3 (Ali et al. 2023).

Introduction

In forest ecology, the influence of species diversity and stand structure diversity (SSD) on aboveground biomass (AGB) has been extensively discussed. There has been intricate discussion about whether species diversity or structural diversity (such as tree diameter and height diversity) has a great impact on AGB or productivity in forest ecosystems (Poorter et al. 2017). While species diversity is a component of stand structural diversity, the latter is typically defined by tree diameter and height diversity, either individually or in combination (Wang et al. 2011). However, both regional-level experimental studies and ecological theories suggest that AGB is primarily influenced by favorable climatic conditions (Currie et al. 2004). Nevertheless, various local-scale ecological mechanisms, including niche complementarity, selection or mass ratio, and competitive exclusion effects, have been proposed to influence the relationships between biodiversity and ecosystem functioning (Poorter et al. 2017). In particular, within natural forest ecosystems, areas with abundant precipitation and favorable water availability tend to exhibit higher species richness (SR) and AGB. (Poorter et al. 2015). Species coexist by exploiting distinct resources across spatial and temporal environmental gradients. This concept, known as niche theory, posits that various species are influenced by different environmental factors due to their unique niches. Consequently, different species may exhibit diverse adaptations to specific environments (Tilman 2004; Weiser et al. 2018).

When examining ecosystems on a broad scale, such as different types of tropical forests, climate has been identified as a significant driver of productivity and biomass stocks (Toledo et al. 2011). However, when we zoom in to smaller scales, it becomes apparent that soil conditions, rather than climate, exhibit greater variability (Burrough 1983). The fertility of the soil is expected to have a positive impact on biomass productivity, especially in forests that grow in extremely poor soils, like the old and leached soils found on the Guiana Shield on the South American continent (Quesada et al. 2011). These soils are notably lacking in nutrients (Kekem et al. 1996). Multiple environmental factors, including light, water availability, and soil nutrients, can influence the distribution, coexistence, and overall biodiversity of species. It is important to emphasize that the relative importance of these factors in shaping biotic interactions can change across different geographical areas and over time (Ali et al. 2019). Consider, for example, that abiotic factors within natural forests play a direct role in shaping the connections between species diversity, variation in tree size, and aboveground biomass at a regional scale (Ali et al. 2020; Poorter et al.

2015; Stegen et al. 2011). Nonetheless, it is essential to acknowledge that topography is a critical factor that influences the spatial patterns of precipitation, temperature, and soil fertility. These variations in topography can, in turn, have repercussions on the diversity, structure, and functioning of forests (Jucker et al. 2018). While various abiotic factors have intricate and nuanced effects on the distribution patterns of species, it is consistently observed that precipitation and temperature exert a more reliable influence on the regional-scale diversity, structure, and aboveground biomass of forests, as compared to the variable impacts of soil fertility (Ali et al. 2020; Poorter et al. 2015; Prado-Junior et al. 2016; Stegen et al. 2011). Even though environmental filtering plays a direct role in shaping species richness and composition (Kraft & Ackerly 2010), the relative and indirect significance of environmental filtering, mediated by competitor trees of varying sizes, remains relatively unexplored. Additionally, it is anticipated that precipitation and temperature can impact both species richness and aboveground biomass either directly or indirectly, mediated by the presence of moderate, medium, and weak competitor trees, or conversely (Ali et al. 2020). However, the big-tree energy hypothesis puts forth the idea that the availability of energy supports the existence of a small number of large-diameter trees. Consequently, this can establish a connection between different aspects of forest diversity and structure, and the overall aboveground biomass (Ali et al. 2020).

Understory trees, shrubs, herbs, and bryophytes are crucial components of forest ecosystems, making significant contributions to overall diversity and ecosystem function. They account for the major part of species richness, influence forest dynamics, and have a profound impact on carbon and nutrient pools within forest soils (Nilsson & Wardle 2005; Gilliam 2007). However, previous research has predominantly overlooked the relationships between biodiversity and ecosystem functioning in the understory layers of trees, shrubs, herbs, and bryophytes within forests. Failing to consider all vegetation strata in forests may lead to misleading conclusions about the strength and patterns of BEF in forest ecosystems. This oversight can result in discrepancies between the aspects of biodiversity and ecosystem function being assessed (Balvanera et al. 2014). The diversity and makeup of the tree community can also serve as a significant biotic factor influencing ecosystem functions such as biomass productivity and stocks (Hooper et al. 2005). For instance, when a system boasts a wide array of species (high species richness), it can enhance resource utilization efficiency through mechanisms likes niche complementarity or species facilitation (Tilman 1999). It is worth noting that research conducted across various systems and at different scales has yielded mixed results regarding the impact of species richness on biomass productivity and stocks. While some studies have identified positive effects (Vilà et al. 2013; Poorter et al.

2015), others have found no or even negative effects (Adler et al., 2011) on biomass productivity and stocks (Chisholm et al. 2013). We anticipate that the potential for niche complementarity to have a substantial impact may be limited under harsh conditions, where only a few species with highly adapted strategies thrive, as is the case in the Guyanese forest with nutrient-poor soils. The differing outcomes observed in studies regarding the effects of diversity on ecosystems could, in part, be attributed to the fact that species richness alone does not offer insights into the functional traits of the species. There is a growing research interest focused on understanding the relationships between forest structure, function, diversity, and soil and climatic conditions across different forest types. This research is important for informing forest management and conservation strategies that are tailored to specific forest types and environmental conditions (Luyssaert et al. 2018). However, there are still significant research gaps in our understanding of these relationships. For example, more research is needed on the impacts of climate change on forest structure, function, and diversity. Additionally, there is a need for more research on the relationships between soil properties and forest structure and function, particularly in regions with diverse soil types.

3.1.1 Hypothetical model

We hypothesize that forest diversity and structure significantly vary along the climatic gradient (mainly temperature and precipitation) and soil across Pakistan. To test our hypothesis we have the following objective, i.e., to describe the relationship between diversity, stand structure, and aboveground biomass along with climate and soil across Pakistan. We collected data from a forest inventory survey comprising 15,260 individuals from 104 different tree species across 200 forest plots. These plots were categorized into five different types of forests. To analyze the data, we employed structural equation modeling, a powerful and comprehensive technique (Figure 1).

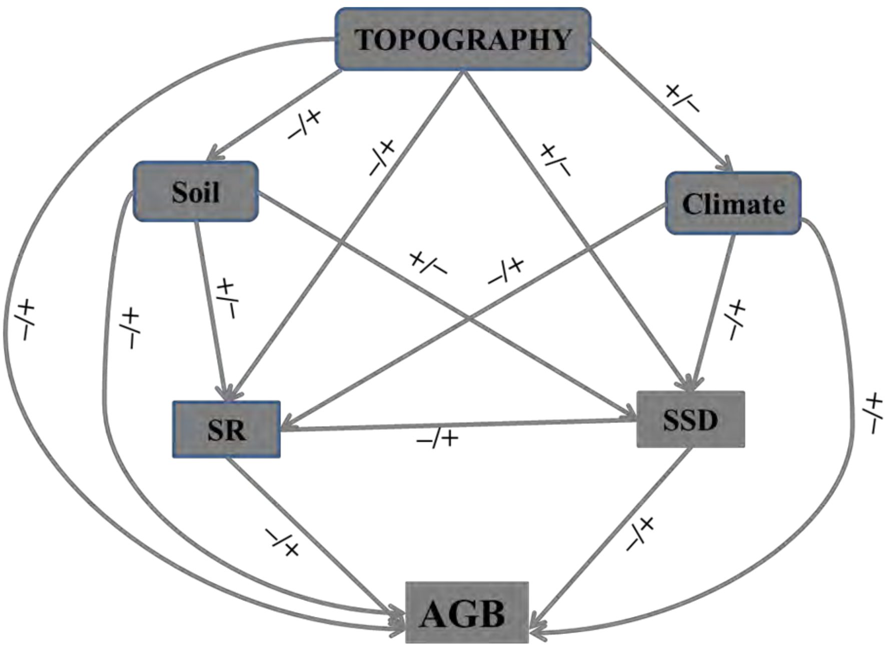


Figure 17 Hypothetical Model explaining the effect of topography, soil, climate, stand structure diversity (SSD), and Shannon diversity (SD) on aboveground biomass (AGB).

Variables with hypothesized relationships are denoted by -, +, or -/+, accordingly. Abbreviations; Topography = slope angle and elevation, SSD= stand structure diversity, SD= Shannon diversity Index, AGB= aboveground biomass.

3.2 Methodology

3.2.1 Forest inventory

Based on forest inventory data (*Chapter 2*) we prepare three dataset i.e., whole community (all strata), overstorey (diameter at breast height≥ 10cm), and understory (diameter at breast height ≤ 10cm). To evaluate the impact of biotic and abiotic variables on aboveground biomass in all three strata across forest types. The dataset includes the biotic variables representing the stand structure diversity (SSD) i.e., diameter at breast height, height, and crown of the plants and Shannon diversity among plants across all forest types. Abiotic variables include topography representing latitude, longitude, sole angle, and elevation of the forest types. Soil representing the soil clay loam percentage, soil carbon nitrogen phosphorus (CNP), other soil macro properties (SMP), such as cobalt, magnesium, calcium, sodium, and soil micro properties (SmP) such as chromium, nickel, copper, and manganese. limate represents the mean temperature, mean precipitation, relative humidity, and wind pressure.

3.2.2 Statistical Analysis

To investigate the impact of the biotic and abiotic variables on above-ground biomass we decouple a structural equation model (SEM). We develop several models to evaluate the impact of biotic and abiotic variables on aboveground biomass in the whole community as well as in overstorey and understory aboveground biomass combined. The goodness of fit (GFI) was assessed using several statistical tests, such as the Chi-squared test, comparative fit index (CFI), standardized root mean square residual (SRMR), Bayesian information criterion (BIC), and Akaike's information criteria (AIC). To determine whether the data were multi-collinear, a variance inflation factor VIF test was performed. The VIF test has roughly 2.50 relevance in our case. Linear regression was employed to determine the complete path measurements of the structural equation modeling (SEM) results for each conceptual path (Figure 17). Scatter plots were used by employing the function plot (x, y) to investigate the relationship between aboveground biomass and structural diversity. The linear models between y and x were fitted using the function lm (). All the analyses were done in R 3.6.3 (Ali et al. 2023).

3.3 Result

3.3.1 Relationship between soil physicochemical properties, diversity, and aboveground biomass (AGB)

An increase in topography led to positive and significant effects on soil macro properties (SMP), soil micro properties, soil carbon nitrogen phosphorous (CNP), stand structure diversity (SSD), and aboveground biomass (AGB), while adverse effects on soil micro properties (SmP), soil clay loam, and Shannon diversity (SD) of the forest respectively. Similarly, SMP, CNP, soil clay loam, and soil micro properties (SmP) was positively correlated to stand structure diversity, Shannon diversity, and aboveground biomass. Stand structure diversity and Shannon diversity also led to a positive effect on aboveground biomass in all forest types. Stand structure diversity also has a positive effect on aboveground biomass productivity (Figure 18 A & B Appendices 1-4).

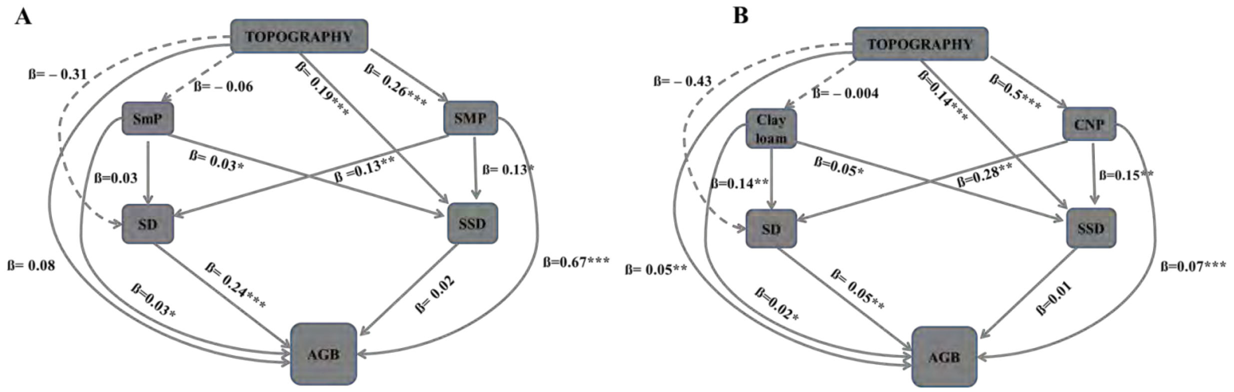


Figure 18 Showing the impact of Topography on soil (i.e., macro properties (SMP), soil micro properties (SmP), soil clay loam, and carbon-nitrogen phosphorous (CNP), stand structure diversity (SSD), and Shannon diversity (SD) on aboveground biomass

(A) Impact of elevation on stand structure diversity (B) Impact of slope on stand structure diversity. The stars represent the level of significance * > 0.05 **> 0.005 and *** represent >0.0005 respectively.

3.3.2 Key models for testing the effect of climate on diversity, stand structure, and AGB

An increase in topography led to a positive impact on mean precipitation (MP) and aboveground biomass (AGB), while an adverse impact on mean temperature (Mt), Shannon diversity (SD), and stand structure diversity (SSD) respectively. Similarly, Mt led to a positive impact on Shannon diversity and aboveground biomass whiles an adverse impact on SSD respectively. An increase in MP led to a positive effect on SD, SSD, and AGB respectively. An increase in SSD, and SD led to a positive effect on AGB in all the forest types (Figure 19 A, Appendices5 & 6). On the other side, an increase in topography led to a positive impact on mean relative humidity (MRH), SSD, and AGB while an adverse impact on mean wind pressure (MWP), and SD respectively. Similarly, MRH and MWP also led to a positive impact on SSD, SD, and AGB respectively. SSD and SD also led to a positive impact on AGB (Figure 19 B, Appendices 7 & 8).

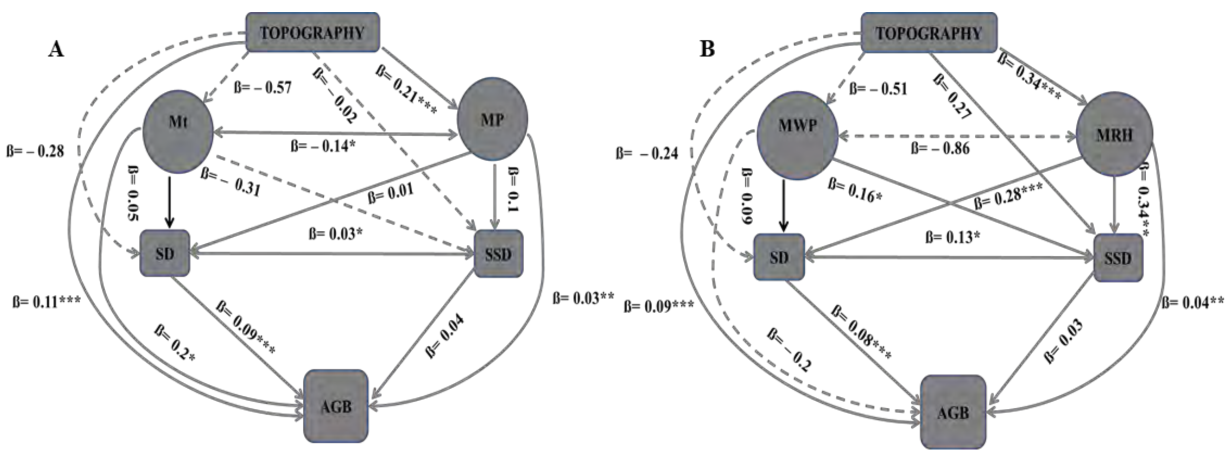


Figure 19 Impact of Topography on climate (i.e. mean temperature (Mt), mean precipitation (MP), mean wind pressure (MWP), and mean relative humidity (MRH)) stand structure diversity (SSD), and Shannon diversity (SD) on Aboveground Biomass (AGB)

(A) Impact of Mt, MP, SSD, and SD on Aboveground Biomass (B) Impact of MWP, MRH, SSD, and SD on Aboveground Biomass. The stars represent the level of significance * > 0.05 **> 0.005 and *** represent >0.0005 respectively.

3.3.3 Key models for testing the effect of soil on diversity, stand structure, and over-story and under-story AGB

Soil rich in clay loam particles has a positive effect on over-story aboveground biomass (OAGB) while an adverse impact on under-story aboveground biomass (UAGB). An increase in soil carbon nitrogen phosphorus (CNP) led to a positive impact on OAGB and UAGB. An increase in over-story stand structure diversity (OSSD) led to a positive effect on OAGB while an adverse effect on UAGB. Similarly, an increase in understorey stand structure diversity (USSD) led positive effect on UAGB while an adverse effect on OAGB. An increase in overstorey Shannon diversity (OSD) led to a positive effect on UAGB but also to adverse effect on OAGB. The increase in understorey Shannon diversity (USD) led to a positive effect on UAGB as well as OAGB respectively (Figure 20 A, Appendices 9 & 10). On the other side, an increase in soil micro properties (SmP) led to a positive effect on OAGB, UAGB, and USSD with an adverse effect on USSD, USD, and OSD respectively. Similarly, an increase in soil macro properties (SMP) led to a positive effect on OAGB, and an adverse effect on UAGB, OSSD, USSD, OSD, and USD respectively. An increase in OSSD also has a positive impact on OAGB and a negative impact on UAGB respectively. An increase in USSD has a positive impact on in enhancement of UAGB while an adverse effect on OAGB respectively. Similarly, an increase in OSD has a positive impact on UAGB and an adverse impact on OAGB respectively. An increase in USD also has a positive impact on UAGB and an adverse effect on OAGB respectively (Figure 20 B, Appendices 11 & 12).

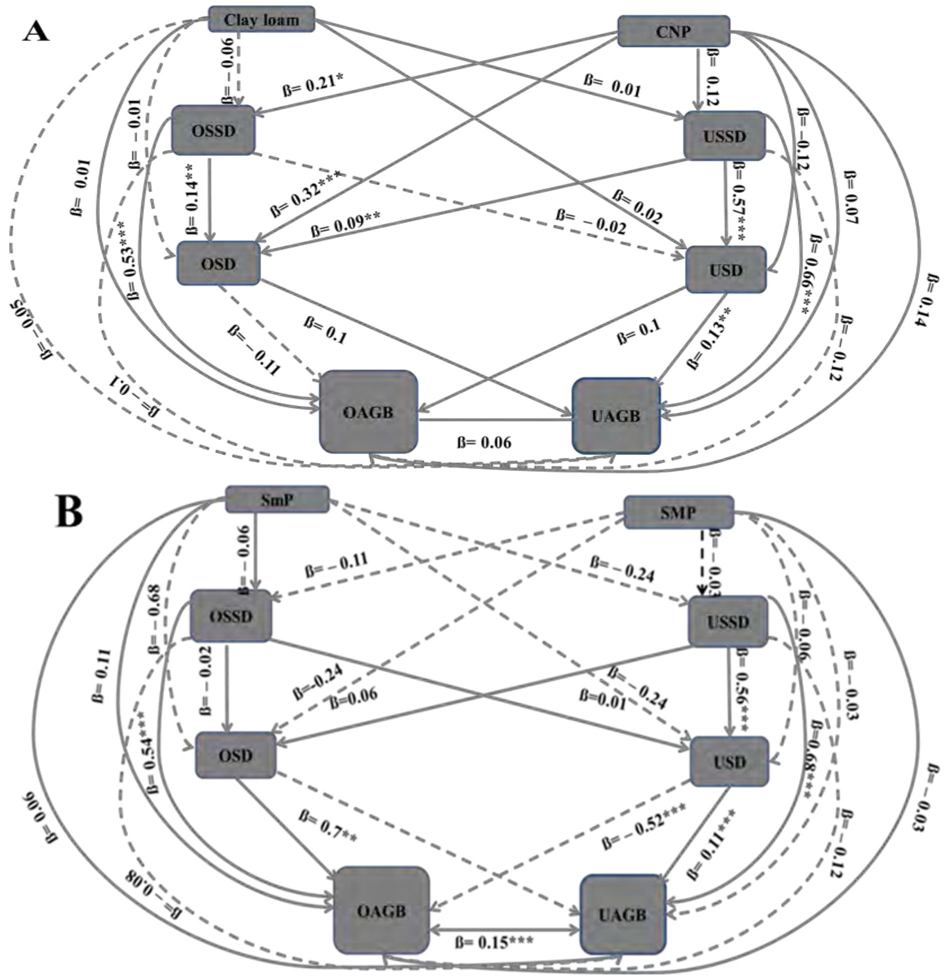


Figure 20 Impact of soil (i.e. soil micro properties (SmP), soil macro properties (SMP), soil clay loam, and carbon-nitrogen phosphorous (CNP), stand structure diversity (SSD), and Shannon diversity (SD) on overstorey aboveground biomass (OAGB), understorey aboveground biomass (UAGB). and understory aboveground biomass.

(A) Impact of SmP and SMP on overstorey stand structure diversity (OSSD), understorey stands structure diversity (USSD), overstorey Shannon diversity (OSD), understorey Shannon diversity (USD) on OAGB and UAGB (B) Impact of clay loam and CNP on OSSD, USSD, OSD, USD on OAGB and UAGB. The stars represent the level of significance * > 0.05 **> 0.005 and *** represent >0.0005 respectively.

3.3.4 Key models for testing the effect of climate on diversity, stand structure, over-story, and under-story AGB

Increased mean precipitation (MP) has a strong significant effect on overstorey aboveground biomass (OAGB) and understorey aboveground biomass (UAGB). Similarly, MP is also a key factor in facilitating understory stand structure diversity (USSD), overstorey Shannon diversity (OSD), and understory Shannon diversity (USD) respectively. While MP significantly affects the growth of overstorey stand structure diversity (OSSD) in all forest types. Similarly, mean temperature (Mt) has a positive and significant effect on OAGB, UAGB, and OSD while having an adverse effect on OSSD, USSD, and USD respectively. The OSSD has a positive effect on OAGB, and OSD with an adverse effect on UAGB and USD respectively. The impact of USSD was recorded as positive on UAGB, USD, and OSD while negative was recorded on OAGB respectively. Similarly, the impact of OSD on UAGB was recorded as positive while negative on OAGB respectively. The impact of USD was recorded as positive on OAGB and UAGB respectively. The impact of OAGB on UAGB was also recorded as positive (Figures 21 A, Appendices13 & 14). On the other side, mean wind pressure (MWP) has a positive impact on OSD and while negative on OAGB, UAGB, USSD, OSSD, and USD respectively. Similarly, mean relative humidity (MRH) has a positive impact on OSSD, USSD, OSD, and USD and a negative impact on UAGB, and OAGB respectively. The impact of OSSD was recorded as positive on OAGB and OSD while a negative impact was recorded on UAGB and USD respectively. The impact of USSD was recorded as positive on UAGB, USD, and OSD while negative was recorded on OAGB respectively. Similarly, the impact of OSD on UAGB was recorded as positive while negative on OAGB respectively. The impact of USD was recorded as positive on UAGB and OAGB \respectively (Figure 21 B, Appendices15 & 16).

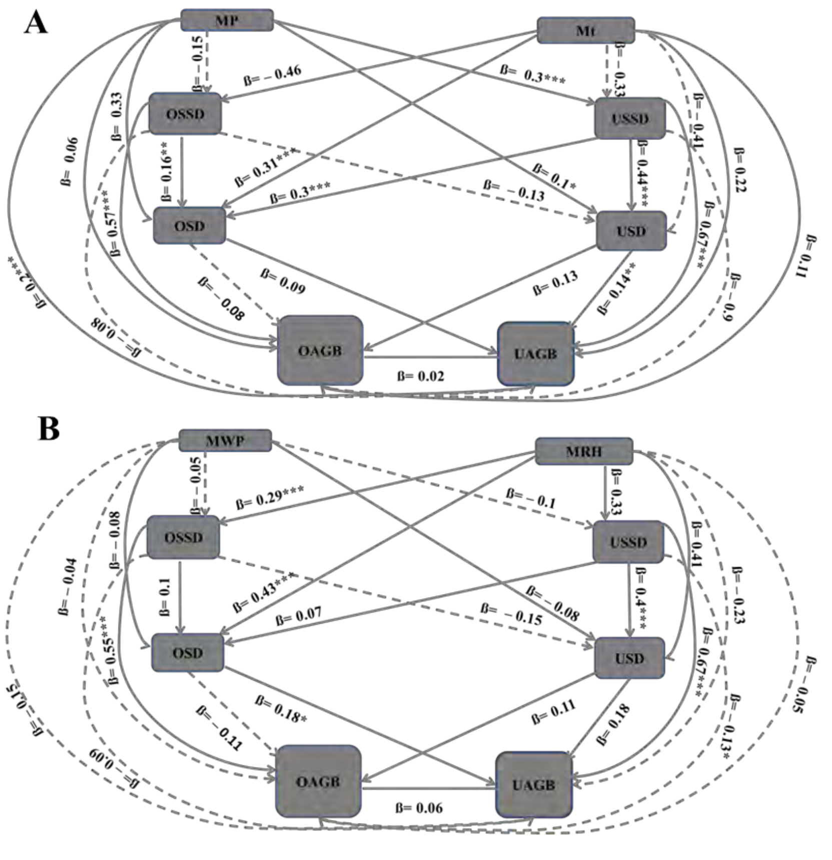


Figure 21 Impact of climate (i.e. mean temperature (Mt), mean precipitation (MP), mean monthly temperature (MWP), mean relative humidity (MRH), overstorey stands structure diversity (OSSD), understorey stands structure diversity (USSD), overstorey Shannon diversity (OSD) and stand structure diversity (USD) on overstorey and understorey AGB

(A) Impact of Mt, MP, SSD, and SD on overstorey and understory Aboveground Biomass (B) Shows the impact of MWP, MRH, SSD, and SD on over and understory Aboveground Biomass. The stars represent the level of significance * > 0.05 **> 0.005 and *** represent >0.0005 respectively.

3.3.5 Scatter plots evaluating the relationship between biotic variables and aboveground biomass (AGB)

The scattered plot shows the relationship between stand structure diversity (i.e. diameter at breast height, height, crown area, and Shannon diversity) with aboveground biomass. The result shows a positive and significant relationship between diameter at breast height, height, crown area, and Shannon diversity) with aboveground biomass (Figure 22).

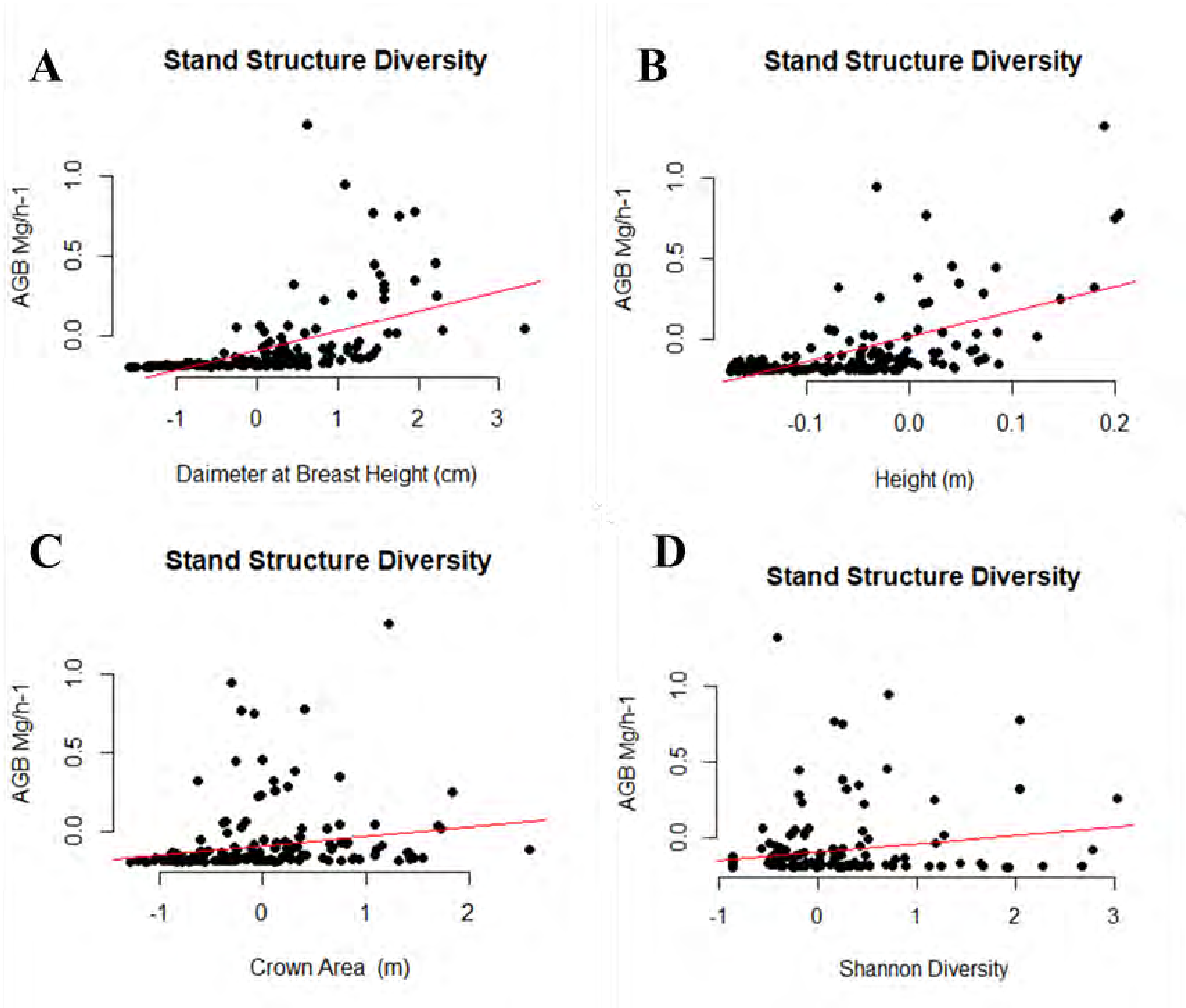


Figure 22 Relationship between stand structure diversity (i.e. diameter at breast height, height, crown area, and Shannon diversity) with aboveground biomass

(A) Relationship between diameter at breast height and aboveground biomass. (B) Relationship between height and aboveground biomass. (C) Relationship between crown area and aboveground biomass. (D) Relationship between Shannon diversity and aboveground biomass.

3.3.6 Scatter plots evaluating the relationship between topography and AGB

The scatter plots show the relationship between topography (i.e., N'Longitude, N'Latitude, elevation, and slope angle) with aboveground biomass. The result shows a positive and significant relationship between N'Longitude, N'Latitude, elevation, and slope angle with aboveground biomass (Figure 23).

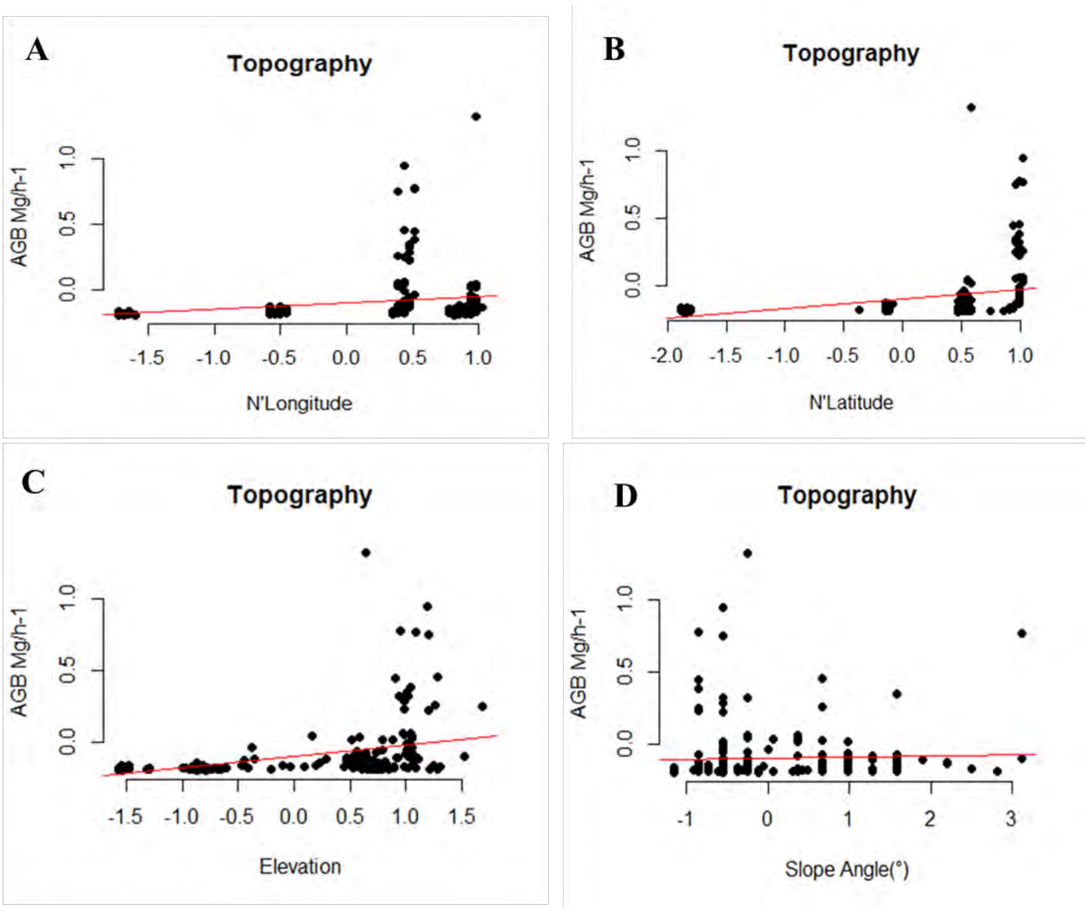


Figure 23 Relationship between topography (i.e. N'Longitude, N'Latitude, elevation, and slope angle) with aboveground biomass

(A) Relationship between N'Longitude and aboveground biomass. (B) Relationship between N'Latitude and aboveground biomass. (C) Relationship between elevation, and aboveground biomass. (D) Relationship between slope angle and aboveground biomass.

3.3.7 Scatter plots evaluating the relationship between soil physicochemical properties and aboveground biomass (AGB)

The scatter plots show the relationship between soil physicochemical properties (i.e., soil clay loam, nitrogen, phosphorus, and organic carbon) with aboveground biomass. The result shows a positive and significant relationship between soil clay loam, nitrogen, phosphorus, and organic carbon with aboveground biomass (Figure 24).

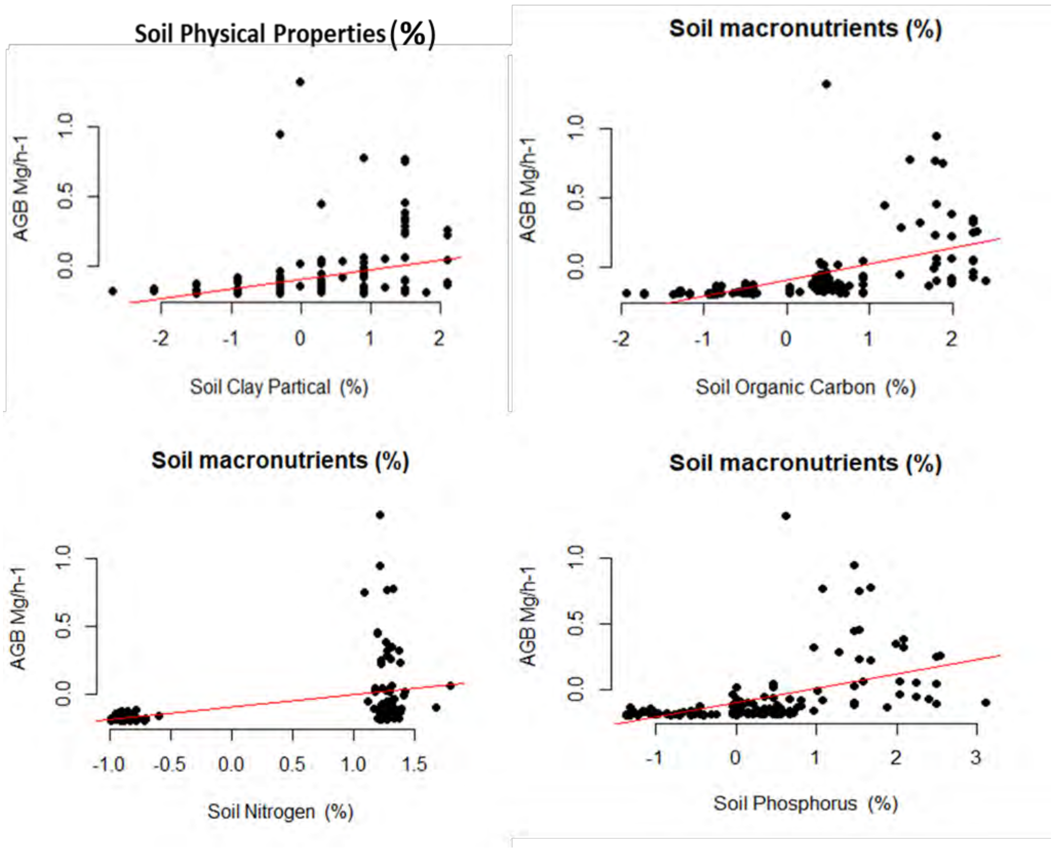


Figure 24 Relationship between soil physicochemical properties (i.e., soil clay loam, organic carbon nitrogen phosphorus (CNP) with aboveground biomass.

(A) Relationship between soil clay loam and aboveground biomass. (B) the Relationship between organic carbon and aboveground biomass. (C) Relationship between nitrogen, and aboveground biomass, (D) the Relationship between phosphorus and aboveground biomass.

3.3.8 Scattered Plot evaluating the relationship between soil macronutrient properties and AGB

The scatter plots show the relationship between soil macronutrient properties (i.e. Soil cobalt, soil sodium, soil calcium, soil chromium) with aboveground biomass. The result shows that soil cobalt and soil sodium have a positive and significant relationship with aboveground biomass. While soil calcium, soil chromium has a negative relationship with aboveground biomass (Figure 25).

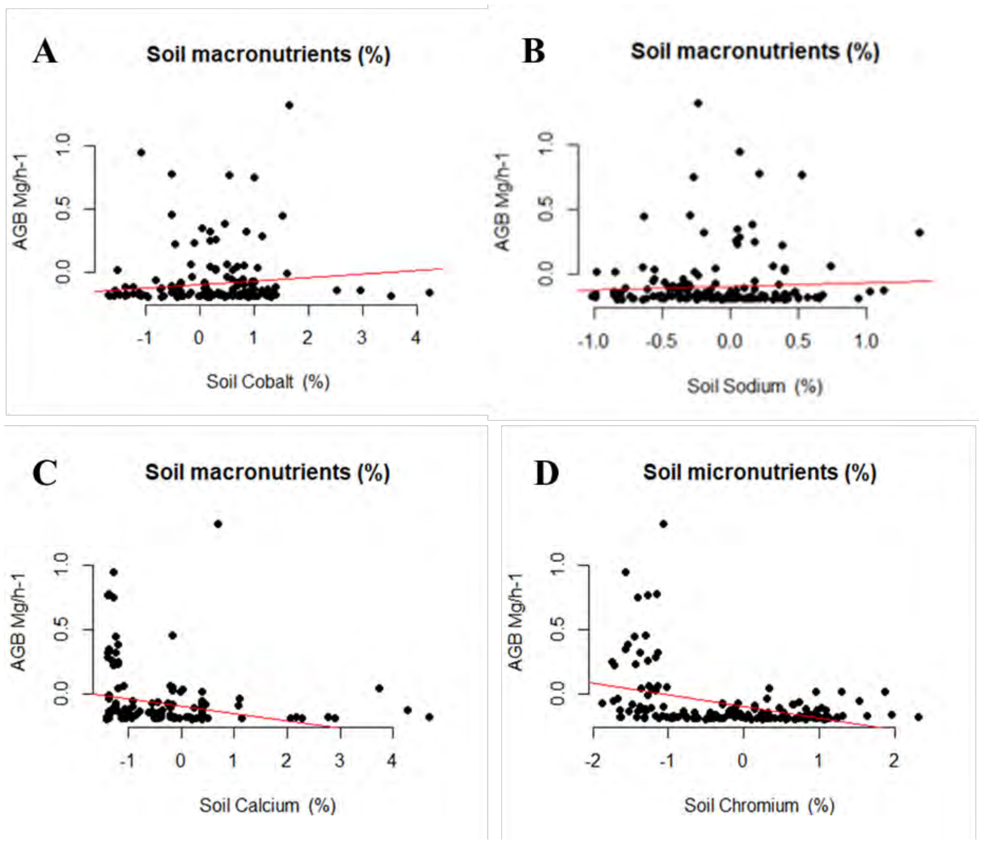


Figure 25 The relationship between soil macronutrient properties with aboveground biomass.

(A) Relationship between soil cobalt and aboveground biomass. (B) Relationship between soil sodium and aboveground biomass. (C) Relationship between soil calcium, and aboveground biomass. (D) Relationship between soil chromium and aboveground biomass.

3.3.9 Scatter plots evaluating the relationship between soil micronutrient properties and AGB

The scatter plots show the relationship between soil micronutrient properties (i.e., manganese, chromium, and nickel, copper) with aboveground biomass. The result shows that manganese has a positive and significant relationship with aboveground biomass, while chromium, nickel, and copper have a negative relationship with aboveground biomass (Figure 26).

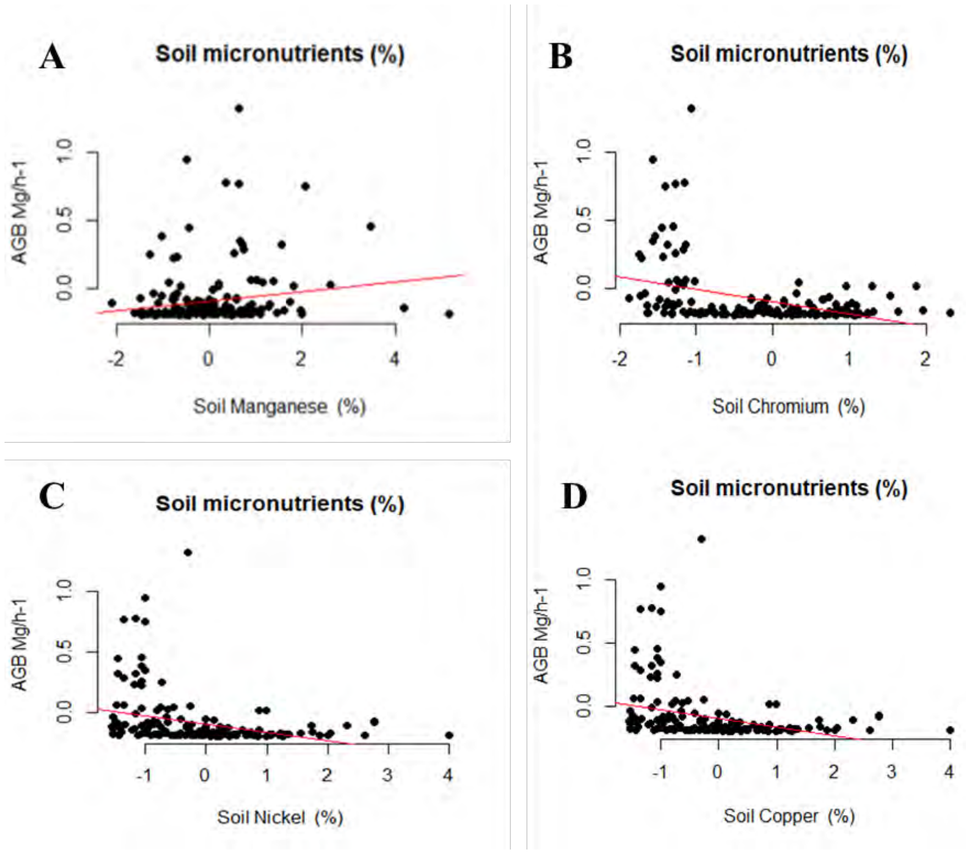


Figure 26 Relationship between soil micronutrient properties with aboveground biomass

(**A**) Relationship between soil manganese and aboveground biomass. (B) Relationship between soil Chromium and aboveground biomass. (**C**) Relationship between soil nickel, and aboveground biomass. (D) Relationship between soil copper and aboveground biomass.

3.3.10 Scatter plots evaluating the relationship between climate and AGB

The scatter plots show the relationship between climate (i.e., mean monthly precipitation, mean monthly relative humidity, mean monthly temperature, and mean monthly wind pressure) with aboveground biomass. The result shows that mean monthly precipitation and mean monthly relative humidity have a positive and significant relationship with aboveground biomass. While mean monthly temperature and mean monthly wind pressure has a negative relationship with aboveground biomass (Figure 27).

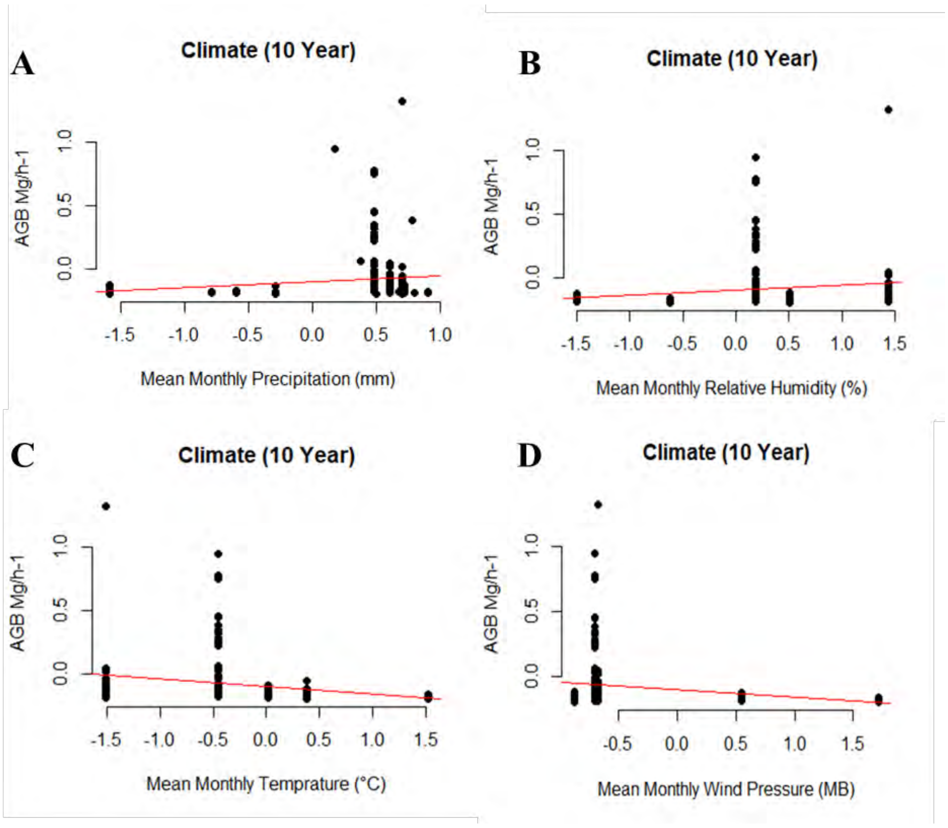


Figure 27 The relationship between climate with aboveground biomass

(A) Relationship between mean monthly precipitation and aboveground biomass. (B) Relationship between mean monthly relative humidity and aboveground biomass. (C) Relationship between mean monthly temperature and aboveground biomass. (D) Relationship between mean monthly wind pressure and aboveground biomass.

3.3.11 Pearson correlation evaluating the overall relationship of biotic and abiotic variables with AGB

The Pearson correlation evaluates the relationship between independent and dependent variables. Overall the result shows aboveground biomass (AGB) is strongly correlated with overstorey aboveground biomass (OAGB). Soil, topography, stands structure diversity (SSD), and Shannon diversity while it is negatively correlated with climate and understory aboveground biomass (UAGB). Similarly, OAGB is strongly correlated with soil, topography, SSD, and Shannon diversity and negatively correlated with UAGB and climate. The SSD is strongly correlated with topography, soil, UAGB, and Shannon diversity, while negatively correlated with climate. Topography is strongly correlated with soil UAGB, while negatively correlated with climate. Similarly, UAGB is positively correlated with climate and Shannon diversity. In last the Shannon diversity is positively correlated with climate (Figure 28).

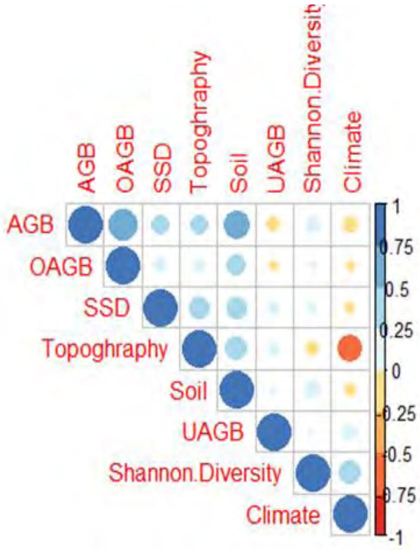


Figure 28 Correlations between biotic and abiotic variables.

3.3.12 The relative contribution of the overall community in AGB

The pie chart evaluates the relative contribution of the overall community. The result shows that SSD has a great 69 % contribution to AGB production followed by the topography, 16 %, the soil, 12 %, climate, 2%, and Shannon diversity 1% respectively (Figure 29).

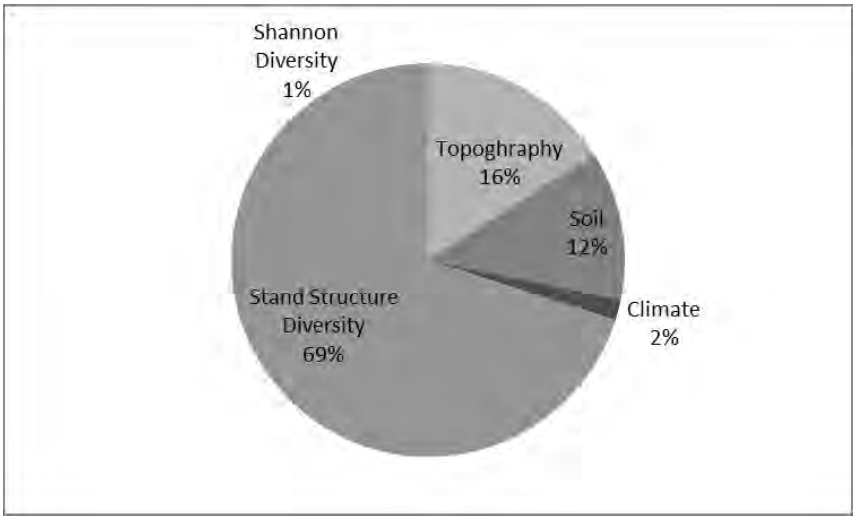


Figure 29 Relative contribution of topography, climate, soil, and stand structure diversity in aboveground biomass of the overall community.

3.4 Discussion

The field of forest ecology has placed significant emphasis on understanding the effects of stand structural diversity and species diversity on the overall functioning of forests. In our investigation of the major forest types across Pakistan, we observed a positive effect of topography soil, SSD, SD, and climate on aboveground biomass.

Impact of topography, stand structure diversity species diversity on aboveground biomass

In the current study, we found a positive impact of topography, stand structure diversity, and species diversity on aboveground biomass This means that topography (i.e., elevation, slope angle, latitude, and longitude) positively affects aboveground biomass. It is known that topography affects the biomass and composition of forests (Whittaker 1956). Their study established that changes in the forest species composition in the Pennsylvanian region of the Ridge and Valley Province could be attributed to elements including parent material, geography, and soil chemistry. These factors were found to be interrelated and showed correlations with one another. It is thought that topographic factors, such as slope angle, elevation, latitude, and longitude influence patterns in the distribution of tree species (McEwan & Muller 2006). The potential for biomass buildup and increased stand structure variety in mid-latitude broad-leaved forests has recently been revealed by research (Pregitzer & Euskirchen 2004). In the current study, we found that topography (i.e., elevation, slope angle, latitude, and longitude) significantly shapes the stand structure diversity (tree DBH, height, crown, and Shannon diversity) of the forest and therefore enhances aboveground biomass. When topography increases the stand structure of the forest also significantly increases. These findings may be due to the nature of the current study which was conducted in different forest types of Pakistan. In our study area, when we move away from the equator towards sub-tropical and temperate region the elevation also increases and significant diversity, stand structure complexity occur which leads to higher aboveground biomass. The sub-tropical thorn forest is in the lower plains and it is exposed to extreme sunlight and winds coming from the Arabian Sea which might negatively affect the stand structure diversity of the forest. In addition, lower stand structure diversity and biomass production may be because these forests are near to equator and there is almost a dry season higher wind pressure lower relative humidity, and less rainfall. In the moist subtropical regions and the temperate regions higher stand structure diversity and biomass are found because these forests are located at a higher elevation and in the mountain ecosystem higher diversity is also found which may lead to higher soil fertility and climate moderation. In tropical Amazonian forests, topography was discovered to have a considerable impact on live tree biomass, while in the Greater Yellowstone ecosystem of the United States; elevation was found to have an impact on the diversity and productivity of forest stand structures (Hansen et al. 2000). Their study (Abrams & Nowacki 1992) established that changes in the forest species composition in the Pennsylvanian region of the Ridge and Valley province could be attributed to elements including parent material, geography, and soil chemistry. These factors were found to be interrelated and showed correlations with one another. Wright

(2002), conducted research at the Coweeta Hydrological Laboratory in western North Carolina they observed that wind throw brought on by storms had several impacts, including the development of pit-and-mound topography, the creation of forest canopy gaps, and the removal of the dense *Rhododendron* maximum understory flora. Because the thermal stability of the photosynthetic machinery at the chloroplast level controls how plants respond to temperature, high temperatures can cause electron transport to be disrupted, induce photoinhibition, and diminish the stability of thylakoid membranes and crucial photosynthetic enzymes (Berry & Bjorkman 1980; Havaux & Environment 1993; Hikosaka 2005; Pearcy 1977; Seemann et al. 1984; Smillie & Nott 1979). Such damage can cause a severe reduction in photosynthesis at high temperatures, even for plants that are well-suited to hot environments. Similarly, we also find higher stand structure diversity in the inner valleys of the temperate forest, i.e., dry temperate conifer forest, dry temperate *Pinus gerardiana* forest, and moist temperate mix forest. These elevated forests are predominantly situated in inner valleys, forming clusters that stretch narrowly towards the peaks. The higher altitude of these mountains may shield the forests from windstorms, creating an environment conducive to prolonged survival. A study by Whitney and Johnson (1984) investigated the impact of an ice storm on various forest stands in southwestern Virginia, using field surveys to assess the damage. Building on these findings, Warrillow and Mou (1999) conducted a subsequent study in the same region, examining the effects of another ice storm. They confirmed the high susceptibility of *Pinus* spp. to damage and observed that the most severe damage occurred on steep slopes with an east-facing aspect, while slopes and valley bottoms experienced comparatively less damage. The topography, i.e., elevation and slope angle protect these forests from windstorms and therefore reach maximum stand structure diversity. McEwan (2011) studied an old-growth forest named Mount Peitungyen and concluded that old-growth forests are known to operate as carbon sinks, which supports these findings. He further elaborated that the forest has biomass amounts comparable to any of the forest types we looked at globally and is topographically shielded from typhoon damage and also discovered a link between variation in stand structure and topography, for example, the topographic aspect had a significant direct impact on the whole community (McEwan et al. 2011). In the current study, we also found higher stand structure diversity in the dry temperate forest. The reason might be that the forests are covered by high mountains and provide a suitable environment for trees for long survival. The effect of topography varies with climate. In sky islands that rise in deserts, it is positive, but in temperate mountains, it is generally negative as far as carbon capture is concerned (DeLucia & Berlyn 1984) vegetation on these mountains has a reverse elevation gradient from the mountains of the North Temperate Zone like the White Mountains of New England. In the sky islands the trees increase in DBH, height, etc. and the elevation increases as the sites are cooler and wetter as elevation increases (Poulos et al., 2008).

A recent study in a Canadian spruce-dominated forest found that stand structure diversity, i.e., tree diameter and height is positively correlated with aboveground carbon stock and stand productivity (Lei et al. 2009; Wang et al. 2011). In a more recent investigation on mixed and uneven-aged forests in southwest Germany, it was discovered that stand structural variation, as gauged by the rise in stand basal area increment, had a favorable impact on stand productivity (Dănescu et al. 2016). Previously conducted research in temperate deciduous forests stated that stand structure characteristics greatly influence aboveground biomass more than species evenness and richness (Fotis et al. 2018). Additionally, by adopting a forest factory strategy, mean forest production in temperate forest stands in Germany increased with stand structure rather than species variety (Bohn & Huth 2017). In this study, we observed that species diversity also has a positive correlation with above-ground biomass, in the moist temperate mixed, dry temperate conifer, and sub-tropical broad-leaved forests, there is higher species diversity and also higher aboveground biomass as compared to other forests, i.e., dry temperate pure *Pinus gerardiana* and sub-tropical thorn forests where species diversity is low and specific plants are adapted to harsh environment. This means that in the species diverse forest species diversity facilitate dominant trees by providing suitable environment for long exposure and aboveground biomass production. Previously reported studies conducted in moist, wet, and dry old-growth forests worldwide found a positive relationship between above-ground biomass and stand structure attributes (Dănescu et al. 2016). The investigation carried out in 59 tropical forests indicated a positive correlation between stand structure diversity attributes, such as tree average diameter and tree density, and aboveground biomass (Poorter et al. 2015). Our earlier research demonstrates that species variety and aboveground biomass are adversely connected with carbon sequestration, but diameter at breast, height, and crown area is positively correlated with stand structure diversity (Ali et al. 2022). The findings of the present study, investigating the connection between topography, stand structure diversity, and aboveground biomass, strongly endorse the idea that topography plays a crucial role in shaping stand structure diversity. As a result, it significantly influences the aboveground biomass in Pakistan's six main forest types.

Impact of climate and soil on aboveground biomass

The current study evaluates the impact of climate and soil on aboveground biomass. We found a positive relationship between climate and soil with aboveground biomass in the different forest types of Pakistan. This means that climate and soil positively correlate with aboveground biomass temperature increasing the length of the growing season and positively correlated with aboveground biomass and also positively correlated with mean annual precipitation leading to the long growing season of vegetation and therefore increasing forest stand structure and above ground biomass (Bohn et al. 2018; Luo 2007; Poorter et al. 2017; Ali et al. 2019b). In the current study, we also found a positive relationship between climate and soil with aboveground biomass. In some cases in poor species forests the effect positive and negative effects have been reported (Bohn et al. 2018; Jump et al. 2006; McMahon et al. 2010; Pan et al. 2013) have been reported. In the current study, we also found that mean relative humidity is negatively correlated with aboveground biomass and these findings are also supported by another researcher i.e. The presence of higher mean annual precipitation has a beneficial impact, while the presence of greater potential evapotranspiration has a detrimental effect on species richness. This suggests that insufficient climatic water availability is accountable for this trend (Ali et al. 2018; Evans et al. 2005; Li et al. 2013). In the current study, we found higher biomass on the site which has higher precipitation and higher relative humidity, i.e., sub-tropical broad-leaved forest and moist temperate mixt forest. These findings are parallel with previous studies such as, the climate being the primary factor that most effectively accounts for the variability in net primary productivity across extensive ecological gradients, as highlighted in the study by Michaletz and colleagues (2018). To delve deeper, ample climatic water availability extends the duration of the growing season for individual trees within a forest stand. Consequently, this extension leads to higher levels of aboveground biomass within the stand, as noted in studies by Toledo et al. (2011) and Poorter et al. (2015).

The current study has shown that soil is an important factor in aboveground biomass production in different forest types. These findings are in agreement with other studies which state, that soil predominantly regulates AGB on a large scale (Ali et al. 2018). We found in the current study that high aboveground biomass is found on nutrient-rich soil these may be linked with higher precipitation which leads to higher diversity and higher soil organic matter a main driver of soil fertility, nutrient storage, and microbial activities (Lal 2005). However, the soil does not directly enhance aboveground biomass but indirectly via stand structure diversity and species diversity (Poorter et al. 2015; Ali & Yan 2017a; Poorter et al. 2017; Michaletz et al. 2018). However, increased availability of soil nutrients can also result in a higher mortality rate, possibly due to heightened interspecific competition in favorable climates. This competition may, in turn, limit the growth of aboveground biomass, as suggested by studies conducted by Paquette and Messier (2011) and Prado-Junior and collaborators (2016). In such a scenario, it becomes understandable that a limited number of dominant, productive, or highly functional species may directly contribute to greater aboveground biomass, primarily due to competitive exclusion effects, as discussed in works by Grime (1973), Ali and collaborators (2016), and Ali and Mattsson (2017b). Consequently, we can anticipate weaker indirect impacts of climate and soil on aboveground biomass through their influence on species diversity.

In this study, we also discovered a relationship between overstory and understory aboveground biomass and we found that overstorey stand structure and diversity negatively correlate with each other These findings are supported by previous studies, i.e., overstory stand structure had a negative effect on the understory layers because over story use the resource efficiently and likely reduce the strength positive effect of the understory stand structure diversity and aboveground biomass (Hooper et al. 2005). The presence of overstorey trees exerts competitive pressures on understory vegetation due to their large size, which alters the availability of resources both above and below ground, including light, water, and space. This impact is particularly noticeable in the shrub and herbaceous layers, as indicated by studies by Gilliam and collaborators (1995), Gilliam (2007), and Mason and collaboratos (2011). This resource filtering likely diminishes the strength of the relationship between species diversity and increased resource utilization in the resource-limited understory environment, following the findings of Hooper and collaborators (2005). In the current study, we showed that environmental drivers affect the understory and overstory vegetation layer in slightly different directions. These findings indicate that the resource filtering imposed by the overstorey not only impacted the robustness of the connections between diversity and above-ground biomass but also influenced how understory layer species richness responded to climate, soil conditions, and stand development, as observed in the research conducted by Zhang and collaborators Taylor (2014).

3.5 Conclusion

We conclude that the aboveground biomass is primarily driven by favorable climatic and soil conditions. Topography shapes rich stand structure diversity and also provides a better environment for trees grown for a long time and plays a pivotal role in higher aboveground biomass production. Soils rich in clay loam, carbon-nitrogen phosphorous and other nutrients such as manganese, sodium, and cobalt have a significant effect on aboveground biomass. Favorable climatic conditions such as higher precipitation and moderate temperature reflect higher aboveground biomass productivity. The relationship between overstorey stand structure diversity and understory stand structure diversity is opposite to each other and vice versa. Shannon diversity also indicates facilitation in higher aboveground biomass productivity. Overall stand structure diversity is facilitated by topography, followed by soil, climate, and Shannon diversity to produce higher aboveground biomass productivity.

Introduction

Forests are complex ecosystems that are influenced by a variety of environmental factors. The relationship between forest diversity, environmental factors, and aboveground biomass has been the subject of extensive research. The relationship between forest diversity, environmental factors, and aboveground biomass in both single-species and multi-species forests is a topic of ongoing research globally. Environmental factors such as soil fertility, water availability, and climate play important roles in determining the aboveground biomass of forests. For example, research has shown that forests located in areas with high rainfall and temperature have higher aboveground biomass than those in drier and colder areas. Studies have also demonstrated that forest diversity influences aboveground biomass. For example, multi-species forests have been shown to have higher aboveground biomass compared to single-species forests due to their greater diversity and functional complementarity. Additionally, research has shown that the composition and abundance of tree species in a forest influence aboveground biomass, with some species having a greater biomass contribution than others (Poorteret et al. 2016). Various ecological tools have been effectively utilized to establish connections between different biotic elements such as biodiversity and stand structure, as well as abiotic factors like climate and soil properties, about aboveground biomass (Poorter et al. 2017). However, both ecological theories and regional-level experimental investigations suggest that climatic conditions play a pivotal role in determining aboveground biomass (Currieet al. 2004; Huxman et al., 2 4; O‘Brien 2006; Gillman. & Wright 2006). Particularly within natural forest ecosystems, areas characterized by high precipitation and ample climatic water availability tend to exhibit elevated biodiversity and aboveground biomass (Poorter et al., 2015; Ali et al. 2018). In such types of forest ecosystems, diversity can significantly boost aboveground biomass production by providing support during challenging ecological conditions rather than in productive environments, which is often attributed to the resilient effect in diverse species of forest ecosystems (Paquette et al. 2021).

Certain studies indicate that complementarity in forest ecosystems may intensify with higher resource availability or favorable climatic conditions, especially when inter-species interactions enhance light absorption or light-use efficiency (Forrester & Albrecht. 2014). In contexts where soil fertility or water availability increases, forests tend to develop larger leaf areas, potentially heightening competition for light. Consequently, interactions that enhance light absorption or light-use efficiency among participating species become increasingly significant. However, in forests on infertile and arid sites, although light-related interactions can notably boost light absorption, they might not strongly contribute to a positive diversity productivity relationship as growth is primarily constrained by other limiting resources. The research by Forrester (2016) revealed intriguing insights into the presence of complementarity effects in diverse nitrogen-fixing species mixtures. Interestingly, these effects were observed independently of site productivity and climatic conditions, contradicting the expectations outlined in the stress-gradient hypothesis. Instead, they were found to be linked to soil nitrogen availability (Forrester 2014). Despite progress, significant knowledge gaps persist in comprehending these relationships. For instance, there's a critical need for extensive research to delve into how climate change and soil related factors influence forest structure and function, as emphasized by Poorter and collaborators in 2016.

Nature blessed Pakistan with a diverse geography and seasonal variability with an elevation range from 0 to 8611 meters above sea level. Therefore, in Pakistan, different types of forests are found which have vegetative diversity and great economic and ecological importance. These forests play a major role in the conservation of local fauna and also provide valuable ecosystem services (Khan 2020). Different types of forests like the sub-tropical thorn forest, sub-tropical broad-leaved forest, moist temperate mixed forest, dry temperate coniferous forest, dry temperate pure *Quercus* forest, and dry temperate pure *Pinus gerardiana* forest are found in Pakistan (Ali et al. 2013). These forests have not previously been studied for their diversity, structure, and functions along the climate and soil conditions, therefore, a huge research gap and opportunity is found to test the relationship between forest diversity structure and function under diverse types of climate and soil condition. For the first time, in the current research, we are focusing on the relationship between forest diversity structure and function in single and multi-species forest types across Pakistan, such as multi-species forests (i.e., sub-tropical broad-leaved forest, moist-temperate mix forest, dry temperate conifer forest) and single species forest (i.e., dry-temperate pure *Pinus garadiana* forest, and dry temperate pur *Quercus* forest).

4.1.1 Hypothetical Model

We developed a hypothetical model and proposed the following research question and hypothesis. First, does stand structure diversity affect aboveground biomass differently in multi-species and single-species forests? We hypothesized that stand structure diversity affects aboveground biomass differently in both single and multi-species forests. Second, does topography affect stand structure diversity, climate, and soil therefore enhancing aboveground biomass in both forest types? We hypothesized, that topography primarily affects stand structure diversity, climate, and soil and therefore enhances aboveground biomass in both single and multi-species forests. Third, do soil nutrients enhance aboveground biomass in multi-species and single-species forests? We hypothesized that soil clay loam, carbon, nitrogen, phosphorous, and macronutrients such as cobalt, magnesium, calcium, and sodium play a key role in aboveground biomass productivity rather than macronutrients such as chromium, nickel, copper, and manganese in both single and multi-species forests. Fourth, does climate have a more important role in determining aboveground biomass than other factors such as stand structure diversity in both single and multi-species forests? We hypothesized, that factors such as mean precipitation, and mean temperature majorly affect aboveground biomass then relative humidity and wind pressure in both single and multi-species forests. To analyze the data, we employed structural equation modeling, a powerful and comprehensive technique (Figure 30).

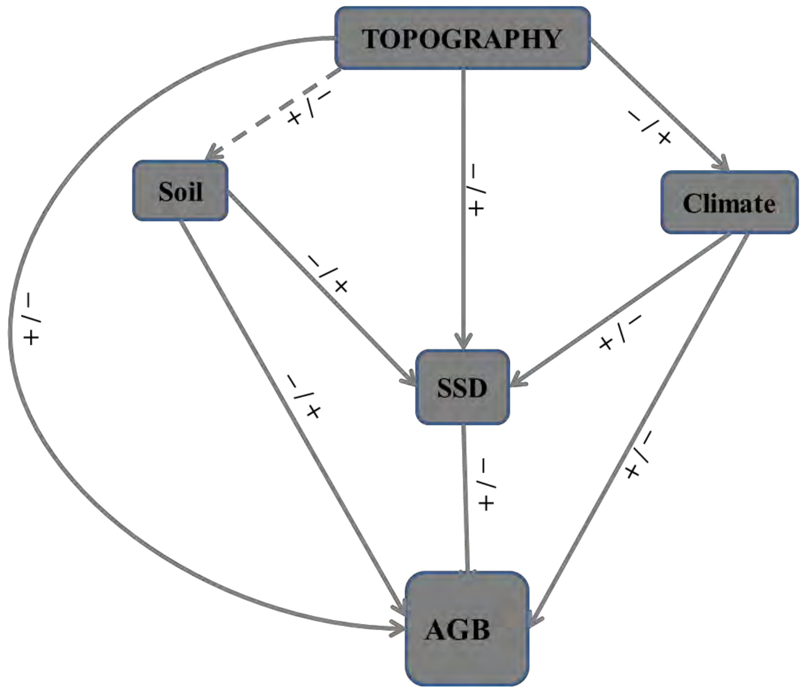


Figure 30 Hypothetical model explaining the effect of topography, soil, climate, and SSD on aboveground biomass.

Variables with hypothesized relationships are denoted by -, +, or -/+, accordingly. **Abbreviations;** Topography = latitude, longitude, slope angle, and elevation, SSD= stand structure diversity, AGB= aboveground biomass, clay loam= soil clay loam particles, CNP= soil carbon, nitrogen, and phosphorus.

4.2 Methodology

To test our hypothesis and answer the research question we collected data from a forest inventory survey comprising 15,260 individuals from 104 different tree species across 200 forest plots (see

Chapter 2 General Methodology for details). These plots were categorized into six different types of nearby forests and two species groups i.e., single species and multi-species forest types. Multi-species forests include subtropical thorn forests, subtropical broadleaved forests, moist temperate mixed forests, and dry temperate conifer forests. Single species forests include dry temperate pure *Pinus gerardiana* forest. The dataset includes the biotic variables representing the structure diversity (SSD), i.e., diameter at breast height, height, and crown of the plants across all forest types. Abiotic variables include topography representing latitude, longitude, sole angle, and elevation of the forest types. Soil representing the soil clay loam percentage, soil carbon nitrogen phosphorus (CNP), other soil macro properties (SMP), such as cobalt, magnesium, calcium, sodium, and soil micro properties (SmP) such as chromium, nickel, copper, and manganese. limate represents the mean temperature, mean precipitation, relative humidity, and wind pressure.

4.2.1 Statistical Analysis

To evaluate the impact of topography, stand structure diversity (SSD) soil (i.e., clay loam, CNP, micronutrients, and macronutrients), and climate such (i.e., mean temperature precipitation relative humidity, and wind pressure) on aboveground biomass in single species forest we developed several structural equation models (SEM). The goodness of fit (GFI) was assessed using several statistical tests, such as the Chi-squared test, comparative fit index (CFI), standardized root mean square residual (SRMR), Bayesian information criterion (BIC), and Akaike's information criteria (AIC). To determine whether the data were multi-collinear, a variance inflation factor (VIF) test was performed. The VIF test has roughly 2.50 relevance in our case. Linear regression was employed to determine the complete path measurements of the structural equation modeling (SEM) results for each conceptual path (Figure 30). Scatter plots were used to evaluate the correlation between environmental variable stand structure diversity and aboveground biomass by employing the function plot (x, y) to investigate the relationship between aboveground biomass and structural diversity. The linear models between y and x were fitted using the function lm (). All the analyses were done in R 3.6.3 (Ali et al. 2023).

4.3 Results

4.3.1 Effect of Soil on stand structure and aboveground biomass in single-species forests

When topography, soil clay loam particles, CNP, and stand structure diversity increase, the biomass also increases in the single-species forest (Figure 31 A, Appendices 17 & 18). On the other side, the structure equation model (SEM) also evaluates that an increase in topography, soil micronutrients, macronutrients, and stand structure leads to higher aboveground biomass productivity in the single species forest (Figure 31 A, Appendices 19, 20).

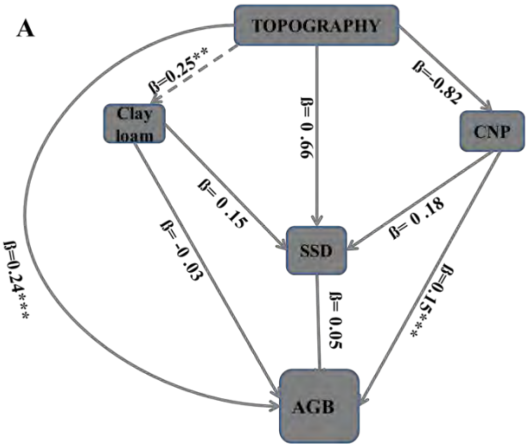


Figure 31 Impact of Topography on soil (i.e., soil micro properties (SmP), soil macro properties (SMP), clay loam, and carbon nitrogen phosphorous (CNP), stand structure diversity (SSD) on aboveground biomass (AGB).

(A) Impact of topography clay loam, CNP, and SSD on AGB (B) Impact of topography, SmP, and SMP on AGB. The stars represent the level of significance * > 0.05 **> 0.005 and *** represent >0.0005 respectively.

4.3.2 Effect of climate on stand structure and aboveground biomass in single-species forests

The structure equation model (SEM) evaluates the impact of topography, climate (i.e., mean temperature (Mt), mean precipitation (MP), mean relative humidity (MRH), and mean wind pressure (MWP), and stand structure diversity (SSD) on aboveground biomass in single-species forests. An increase in topography, SSD, and mean monthly precipitation leads to higher aboveground biomass productivity while an increase in mean monthly temperature leads to a decline in aboveground biomass productivity (Figure 32 A, Appendices21 & 22). On the other side an increase in topography, mean monthly wind pressure, mean monthly relative humidity, and stand structure diversity leads to higher aboveground biomass productivity respectively (Figure 32 A, Appendices23 & 24).

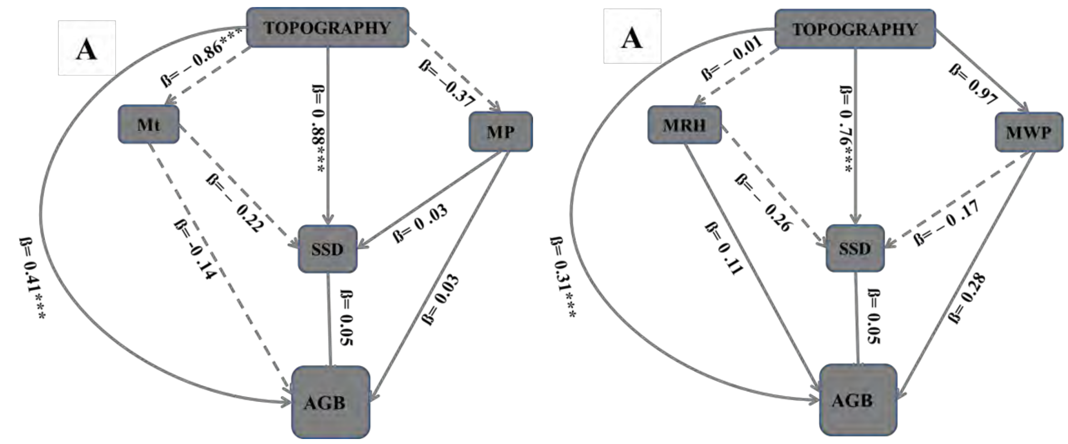


Figure 32 Impact of topography on climate (i.e., mean temperature (Mt), mean precipitation (MP), mean relative humidity (MRH), and mean wind pressure (MWP), stand structure diversity (SSD) on aboveground biomass (AGB).

(A) Impact of topography Mt, MP, and SSD on AGB. (B) Impact of topography, MRH, and MWP on AGB and SSD. The stars represent the level of significance * > 0.05 **> 0.005 and *** represent >0.0005 respectively.

4.3.3 The effect of soil on stand structure and aboveground biomass in multi-species forests

When topography, soil carbon nitrogen phosphorous (CNP), and stand structure diversity (SSD) increase the aboveground biomass (AGB) also increases. The increase in soil clay loam leads to a decline in aboveground biomass in the multi-species forest (Figure 33 A, Appendices25 & 26). Similarly, on the other side, the structure equation model (SEM) also demonstrates that an increase in topography, soil micronutrients (SmP), macronutrients (SMP), and stand structure leads to higher aboveground biomass productivity in the multi-species forest (Figure 33 B, Appendices27 & 28).

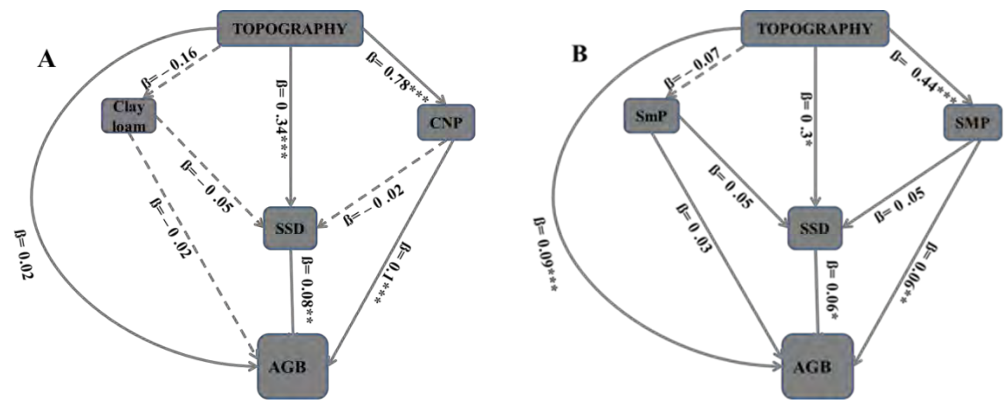


Figure 33 Impact of topography on soil (i.e., soil microproperties (SmP), soil macroproperties (SMP), clay loam, and soil carbon nitrogen phosporous (CNP), stand structure diversity (SSD) on aboveground biomass (AGB) in multi-species forest.

(A) Impact of topography clay loam, CNP, and SSD on AGB. (B) Impact of topography, SmP, and SMP on AGB. The stars represent the level of significance * > 0.05 **> 0.005 and *** represent >0.0005 respectively.

4.3.4 The effect of climate on stand structure and aboveground biomass in multi-species forests

An increase in topography, stand structure diversity (SSD), mean precipitation (MP), and mean monthly temperature (Mt) led to higher aboveground biomass (AGB) productivity (Figure 34 A, Appendices29 & 30). On the other side, an increase in topography, mean relative humidity (MRH), and stand structure diversity led to higher aboveground biomass productivity respectively. An increase in mean wind pressure (MWP) led to a decline in aboveground biomass productivity (Figure 34 A, Appendices31 & 32).

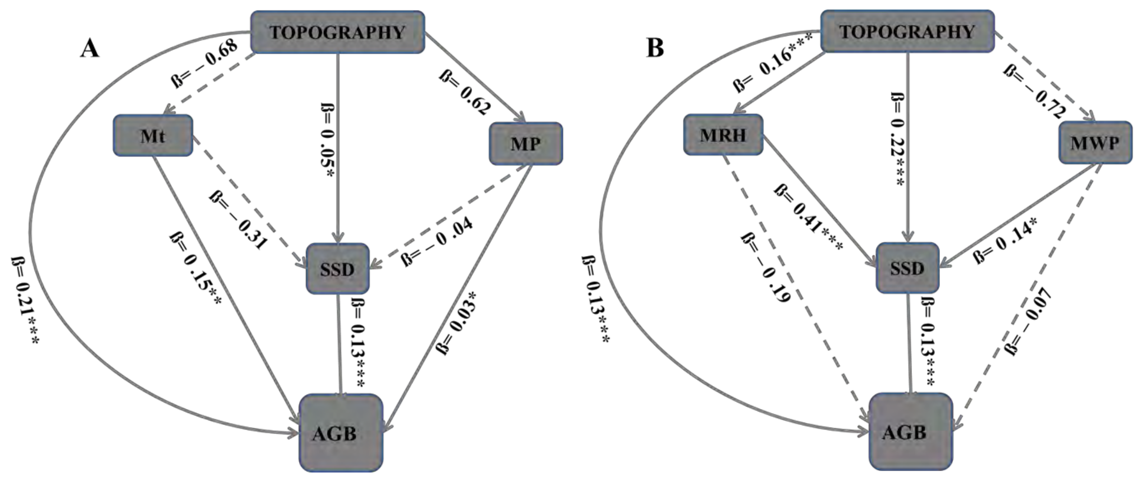


Figure 34 Impact of topography on climate (i.e., mean precipitation (MP), mean monthly temperature (Mt), mean relative humidity (MRH), mean wind pressure (MWP), and stand structure diversity (SSD) on aboveground biomass (AGB).

(A) Impact of topography Mt, MP, and SSD on AGB. (B) Impact of topography, MRH, and MWP on AGB and SSD. The stars represent the level of significance * > 0.05 **> 0.005 and *** represent >0.0005 respectively.

4.3.5 The relationship between stand structure diversity and aboveground biomass in single and multi-species forests

When stand structure diversity increases the aboveground biomass also increases in both single and multi-species forest types (Figure 35).

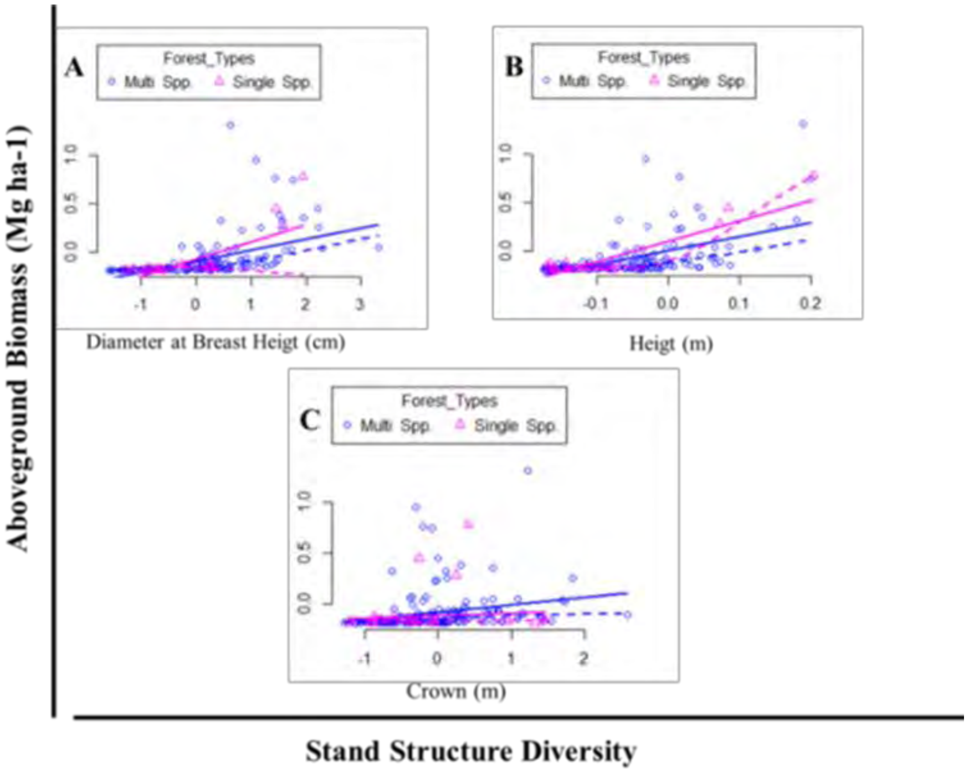


Figure 35 Relationship between stand structure diversity and aboveground biomass in single and multi-species forests

(A) Relationship between diameter at breast height and aboveground biomass. (B) Relationship between height and aboveground biomass. **(**C) Relationship between tree crown and aboveground biomass. The pink line indicates single-species forests while the blue line represents the multi-species forests.

4.3.6 The relationship between topography and aboveground biomass in single- and multi-species forests

An increase in topography leads to higher aboveground biomass productivity in both single and multi-species forests except where an increase in slope angle leads to a decline in aboveground biomass productivity in single-species forests (Figure 36).

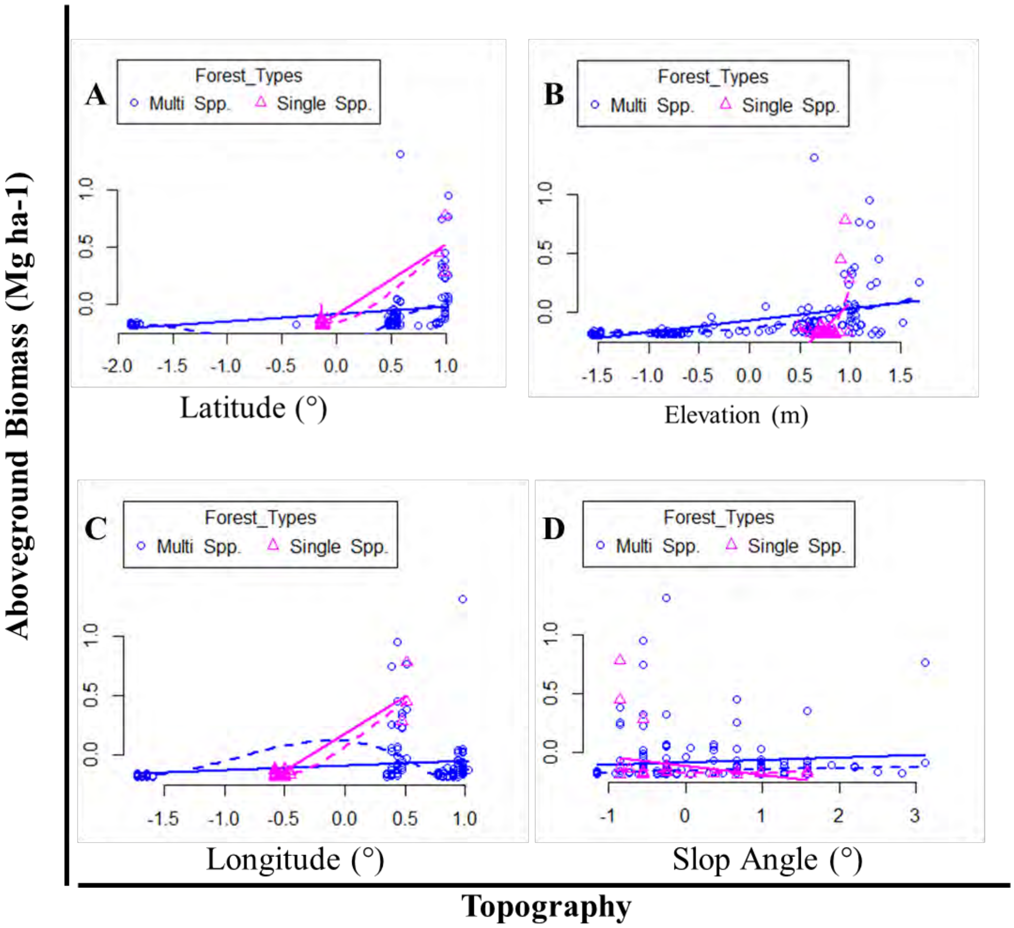
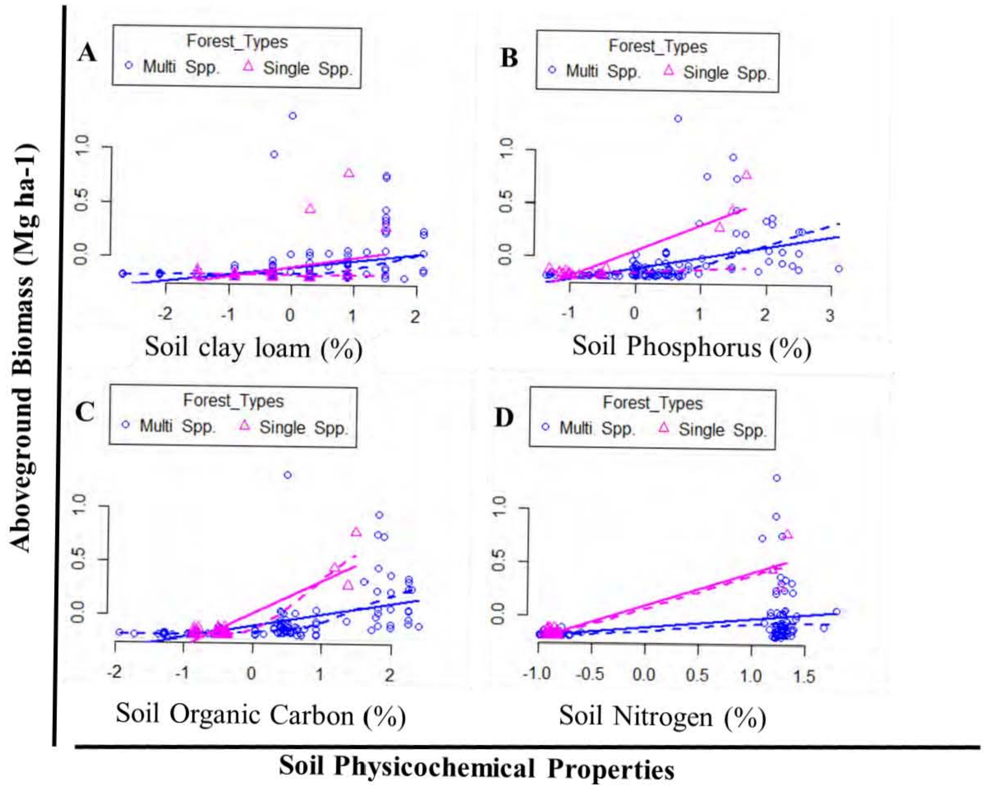


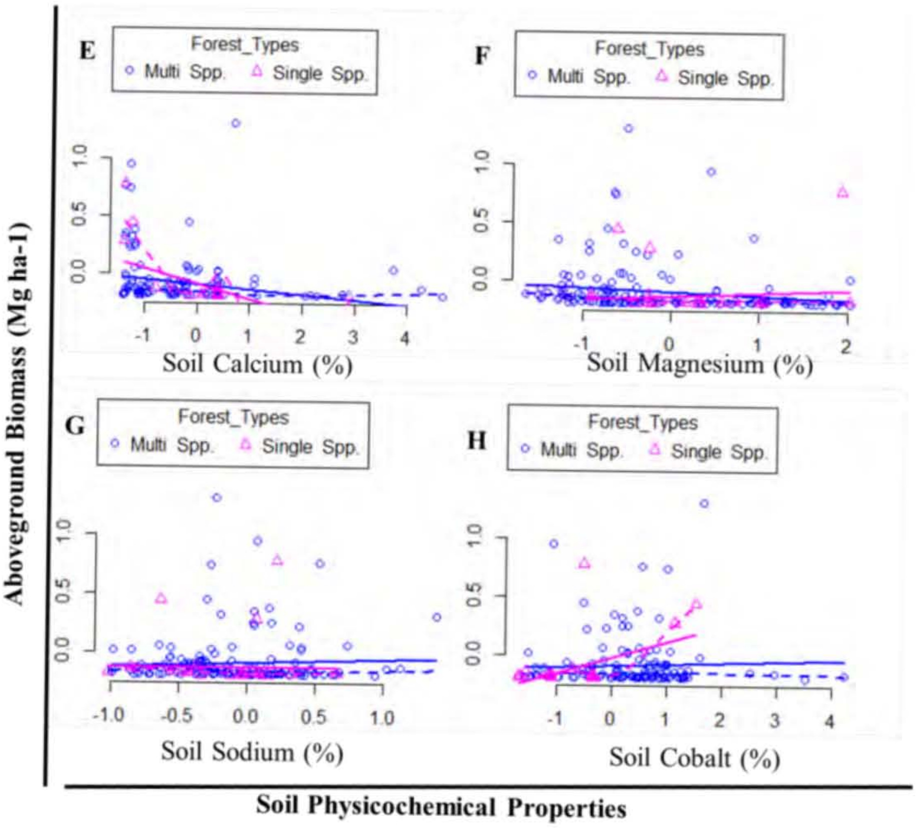
Figure 36 Relationship between topography and aboveground biomass in single and multi-species forests.

(A) Relationship between latitude and aboveground biomass. (B) Relationship between elevation and aboveground biomass. (C) Relationship between longitude and aboveground biomass. (D) Relationship between slope angle and aboveground biomass. The pink line indicates single-species forests while the blue line represents multi-species forests.

4.3.7 The relationship between soil physicochemical properties and aboveground biomass in single and multi-species forests

An increase in soil clay loam, phosphorus, organic carbon, nitrogen, sodium, cobalt, and copper leads to an increase in aboveground biomass productivity. The increase in soil magnesium, calcium, nickel, and chromium, leads to a decline in aboveground biomass productivity in both single and multi-species forest types. On the other side increase in soil, magnesium leads to an increase in aboveground biomass productivity in single-species forests while leading to a decline in aboveground biomass productivity in multi-species forests (Figure 37).


A
B
C
D
Forest_Types
Multi Spp.
Single Spp.
Aboveground Biomass (Mg ha-1)
Soil clay loam (%)
Soil Phosphorus (%)
Soil Organic Carbon (%)
Soil Nitrogen (%)
Soil Physicochemical Properties


E
F
G
H
Forest_Types
Multi Spp.
Single Spp.
Aboveground Biomass (Mg ha-1)
Soil Calcium (%)
Soil Magnesium (%)
Soil Sodium (%)
Soil Cobalt (%)
Soil Physicochemical Properties

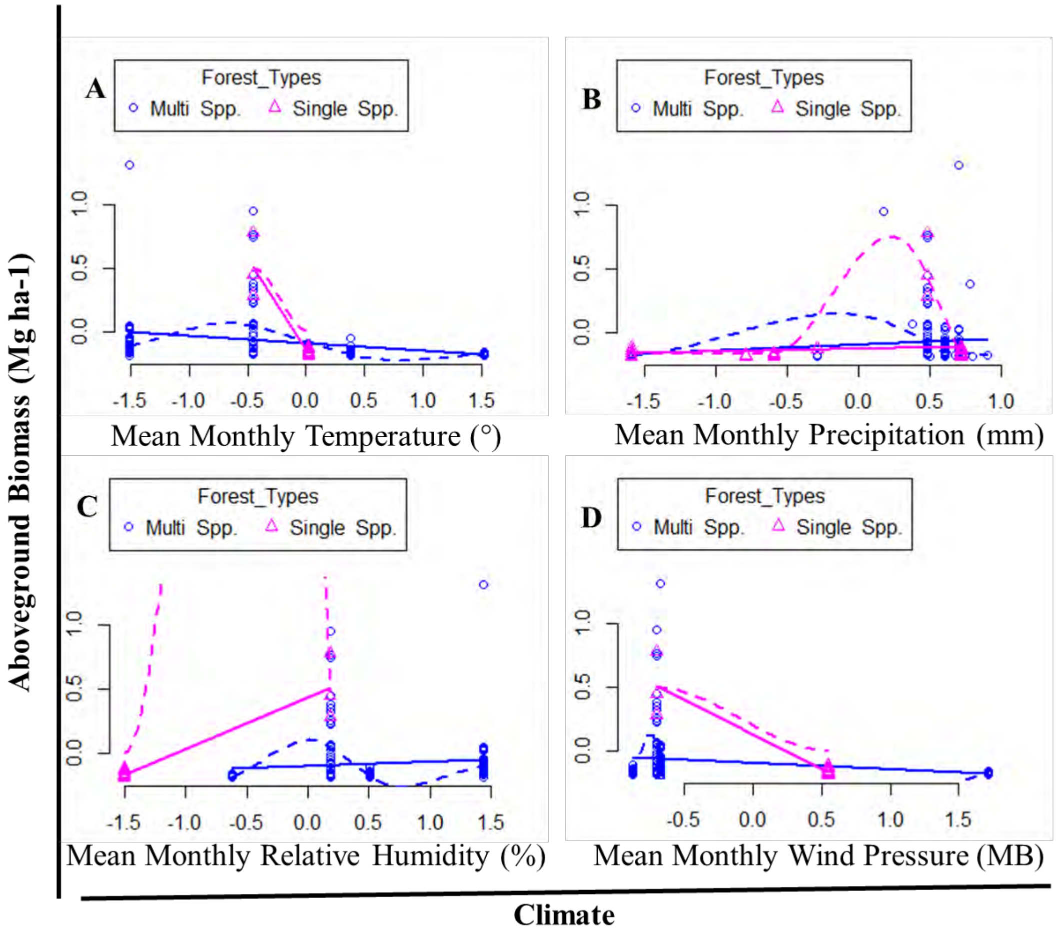


Figure 38 Relationship between climate and aboveground biomass in single and multi-species forests.

(A) Relationship between mean monthly temperature and aboveground biomass. (B) Relationship between mean monthly precipitation and aboveground biomass. (C) Relationship between mean monthly relative humidity and aboveground biomass. (D) Relationship between mean monthly wind pressure and aboveground biomass. The pink line indicates single-species forests while the blue line represents multi-species forests.

4.3.9 Overall relationship of biotic and abiotic variables of aboveground biomass in the single and multi-species forests

Aboveground biomass increases with an increase in soil physiochemical properties followed by stand structure diversity, topography, and climate respectively in the single-species forest. In multi-species forests, it increases with an increase in soil, followed by topography and stand structure diversity while decreasing with climate (Figure 39).

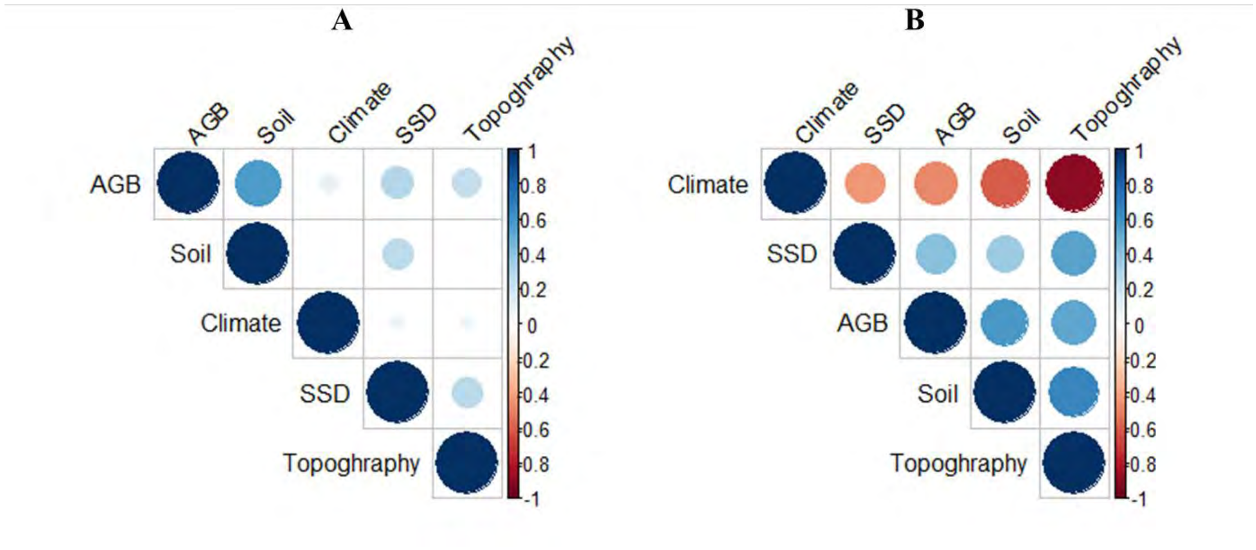


Figure 39 Pearson correlation of the overall relationship of biotic and abiotic variables of aboveground biomass in the single and multi-species forests

(A) Relationship between biotic and abiotic variable in single species forests. (B) Relationship between biotic and abiotic variable multi-species forest.

4.3.10 The relative influence of the overall community in aboveground biomass in the single and multi-species forests

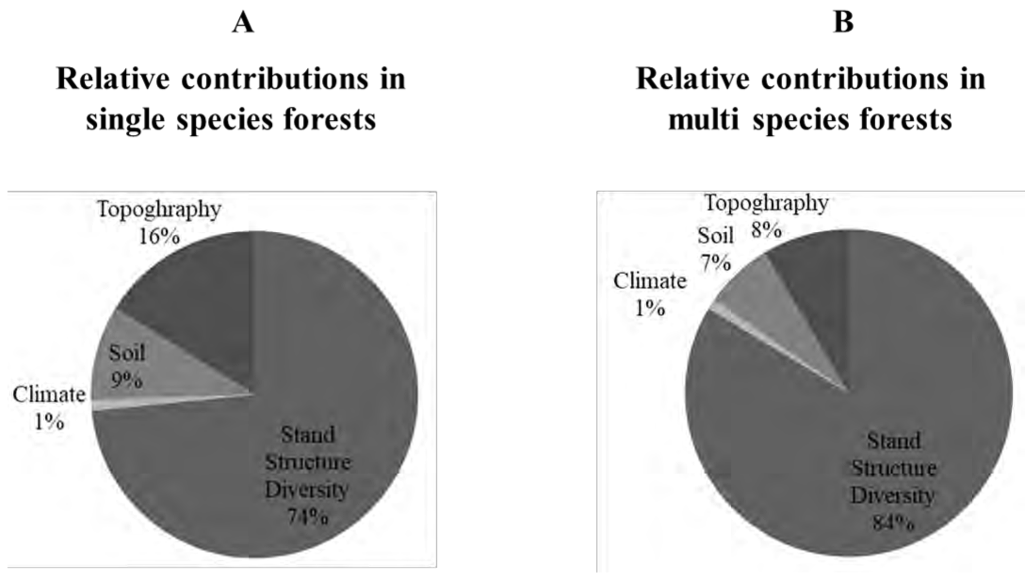


Figure 40 The relative influence of the biotic and abiotic variables in aboveground biomass in the single and multi-species forests.

(A) The relative influence of biotic and abiotic variables in single species forest (B) Relative influence of biotic and abiotic variables in multi-species forest.

4.4 Discussion

Aboveground biomass increases with an increase in stand structure diversity in both forest types and there is no role in the diversity or species composition of the forest. It is well known that stand structure diversity increases aboveground biomass production in the natural forest ecosystem (Ali et al. 2023; Wang et al. 2011). However, most of the studies revealed that multi-species forests produced more aboveground biomass than single-species forests (Schuler et al. 2017). A similar relationship exists in both forests in that the relationship of multi-species forest with aboveground biomass is based on the soil and climatic condition of the particular forest site which increases the diversity of the forest as well as the number of stems density which may lead to higher aboveground biomass production. There is a positive relationship between topography and aboveground biomass in both the single and multi-species forests except the slope angle through which aboveground biomass decreases in the single-species forest and answer to the second research question. This means that topography (i.e. elevation, slope angle, latitude, and longitude) increases the stand structure diversity and therefore enhances aboveground biomass in both the forest types and slope angle decreases the aboveground biomass productivity in the single-species forest. because the single species forest is found in the mountain ecosystem having high peaks and when the slope angle increases a decrease occurs in aboveground biomass productivity. These finding may be due to the nature of the current study the current study was conducted in different forest types of Pakistan and when we move away from the equator towards sub-tropical and temperate region the elevation also increase and significant diversity, stand structure complexity occur which leads to higher aboveground biomass. It is known that topography affects the biomass and composition of forests (Whittaker 1956) and that aboveground biomass significantly increases with an increase in topography (Pregitzer & Euskirchen 2004). These findings support the results of the current study.

Ecological theories and regional-level experimental studies indicate that climatic conditions mainly determine aboveground biomass (AGB) (Currie et al. 2 4; Huxman et al. 2 4; O'Brien 2006; Gillman & Wright 2006). Especially in the natural forest ecosystem, higher diversity and AGB are usually experienced in regions with high precipitation and climatic water availability (Poorter et al . 2015; Ali et al. 2018). The results of the current study support our hypothesis that soil and climate determined aboveground biomass rather than the stand structure diversity of the forests. We evaluate the relationship between forest diversity structure and function along with soil and climate in single and multi-species and found that soil available nutrients and climate primarily determine aboveground biomass in single and multi-species forests. The findings of the study revealed that soil and climate similarly affect aboveground biomass in both single and multi-species forests. This means that aboveground biomass is primarily driven by biotic factors, such as climate and soil rather than species diversity. These findings are supported by previous studies. In essence, when soil fertility or water availability rises, forests tend to have larger leaf areas, likely heightening competition for light. Consequently, interactions that enhance light absorption or light-use efficiency among the species involved could become notably significant. However, in forests situated in infertile and arid sites, even though light-related interactions can indeed enhance light absorption significantly, they might not strongly contribute to a positive diversity-productivity relationship in such locations. This is because growth is primarily constrained by other limited resources (Forrester & Albrecht 2014). Interestingly in this study, we evaluated the climatic factors and found that the increase in precipitation and relative humidity of the aboveground biomass also increased in both single and multi-species forests. Similarly, an increase in temperature and wind pressure leads to a decrease in aboveground biomass. These results provide evidence that climate primarily controls aboveground biomass productivity in both single- and multi-species forests. This means that climatic factors are more important than the diversity of the forest. According to Chazdon (2014), environmental factors such as soil fertility, water availability, and climate play important roles in determining the aboveground biomass of forests. For example, forests located in areas with high rainfall and temperature has higher aboveground biomass than those in drier and colder areas (Chazdon 2014). In natural forests, high species diversity and aboveground biomass are generally located in areas having high precipitation or climatic water availability; these findings support the results of the current study (Poorter et al. 2015; Liang et al. 2016; Ali et al. 2018). We also evaluate the relationship between soil and forest productivity in single and multi-species forests and found that the effect of soil on aboveground biomass is similar in both forest types as soil fertility increases aboveground biomass also increases. This means that soil fertility is responsible for higher aboveground biomass productivity. These findings are in agreement with other studies that soil predominantly regulates AGB on a large scale (Ali et al. 2018). We found in the current study that high aboveground biomass is found on nutrient-rich soil these may be linked with higher precipitation which leads to higher diversity and higher soil organic matter a main driver of soil fertility, nutrient storage, and microbial activities (Lal 2005). These findings are in support of the current research work. The current studies answer all the research questions and improve our understanding of the climate and soil conditions that enhance stand structure diversity in both the single and multi-species forests in similar ways and therefore increase aboveground biomass productivity in the natural forest ecosystem.

4.5 Conclusion

Climate mainly precipitation and relative humidity, and soil such as soil clay loam, carbon, nitrogen, phosphorus, and other macro and micronutrients enhance stand structure diversity, i.e., tee height, diameter at breast height, and crown and therefore regulate aboveground biomass similarly in both single and multi-species forests. Similarly, increases in abiotic variables such as climate and soil directly lead to an increase in aboveground biomass productivity in both forest types. We conclude that in the natural forest ecosystem climate and soil enhance stand structure diversity and determine aboveground biomass in single and as well as in multi-species forests.

Introduction

Large-sized trees (i.e., greater DBH, large height, and big crown) make up roughly 50% of the aboveground biomass in natural forests worldwide. This substantial presence grants them considerable influence over both the abiotic and biotic aspects of forest carbon sequestration and storage (Lutz et al. 2018; Stephenson et al. 2014). It is crucial to acknowledge the substantial role that a few large-diameter trees play in forest diversity, structure, and overall functionality. This is because these larger trees require decades or even centuries to establish themselves in the forest canopy in comparison to medium- and small-sized trees (Ali et al. 2018; Lindenmayer & Laurance 2017; Lutz et al. 2018; Slik et al. 2013). The significance of big trees extends to their role in providing shelter to numerous organisms (Lindenmayer et al. 2012; Remm & Lõhmus 2011), influencing forest dynamics and regeneration (Harms et al. 2000; Rutishauser et al. 2010), as well as total biomass (Stegen et al. 2011). Moreover, large trees are substantial contributors to the global carbon cycle (Meakem et al. 2018). The presence of large-diameter trees is what sets the structural characteristics of primary forests and mature secondary forests apart (Spies & Franklin 1991). Despite their sparse occurrence in terms of stem density, these large-diameter trees significantly influence spatial arrangements across considerable distances between them (Das et al. 2018; Enquist et al. 2009). The significance of large trees is well understood concerning forest structure, biodiversity, and overall functioning (Lutz et al. 2018; Slik et al. 2013). Understanding the dynamics of large-diameter trees hinges on at least two key factors: (a) the existence of species capable of achieving significant size, and (b) environmental conditions, including disturbance patterns, conducive to the growth of such large-diameter individuals. When a forest harbors a diverse array of species capable of attaining large sizes, it becomes more resilient and adaptive to disturbances (Musavi et al. 2017), ensuring the maintenance of its structural integrity and ecological function. Conversely, in scenarios where the diversity of large-diameter species is limited, a forest becomes vulnerable to any alterations affecting these few critical species.

Previous research has established that a substantial proportion of a forest's biomass is composed of large-diameter trees (Clark & Clark 1996; Lutz et al. 2012). Specifically, within forest ecosystems, these big-sized trees, relative to their medium- and small-sized counterparts, constitute a significant part of the aboveground biomass. This, in turn, exerts influence over various aspects such as stand-level leaf area, understory diversity and functions, microclimate, and water utilization (Lutz et al. 2018; Stephenson et al. 2014). The role of large-diameter trees extends to their significant contribution to reproduction (van Wagtendonk & Moore 2010) and their influence on the rates and patterns of regeneration and succession (Keeton & Franklin 2005). Moreover, these trees restrict light and water availability for smaller trees (Binkley et al. 2010) and affect rates and causes of mortality for smaller individuals through events like crushing or injuring sub-canopy trees when their trunks or branches fall to the ground (Chao et al. 2009; Das et al. 2016). It is important to note that alterations in climate, disturbance patterns, and logging activities are accelerating the decline of large-diameter trees (Bennett et al., 2015; Lindenmayer et al. 2012). Moreover, large-sized trees play a critical role in restricting light, water, and soil nutrient availability for the remaining trees. This limitation significantly influences species diversity and the dynamic processes of biomass in natural forests (Ali et al. 2018; Messier et al. 1998). An exclusive focus on plant diversity might overlook the profound impact that dominant species can have on ecosystem functioning (Lohbeck et al. 2016). The mass-ratio hypothesis proposes that ecosystem functions are heavily influenced by the traits of dominant species within stands. These traits can be effectively captured through trait composition and quantified using the community-weighted mean (CWM) of trait values (Grime, 1998). Understanding that highly productive stands primarily composed of fast-growing species might store a lower maximum aboveground biomass (AGB) compared to slow-growing species is crucial. This phenomenon is likely due to the strategy of growing quickly and having a shorter lifespan (Caspersen & Pacala 2001; Prado-Junior et al. 2016). Consequently, the impact of trait composition on forest demographic processes relies on the specific traits being considered. For example, stands dominated by trees with traits that emphasize acquisition (e.g., high specific leaf area) may positively influence demographic processes. Conversely, stands characterized by conservative trait values may exert a negative effect on forest demography (Ruiz-Benito et al. 2014).

In natural forest ecosystems, environmental variables like topography and soil play a crucial role as primary influencers of large-diameter trees, plant diversity, composition, and the dynamics of forest biomass. These factors determine the availability of resources essential for the growth and survival of trees (Paoli et al. 2008; Jucker et al. 2018). It is noteworthy that large-diameter trees need several decades or even centuries to reach maturity and to reach the forest canopy. Consequently, they are more susceptible to environmental shifts worldwide compared to the understory and sub-canopy trees, being directly exposed to variations in air humidity, solar radiation, wind intensity, and seasonal temperature fluctuations. For instance, large-diameter trees with access to deep water tables may display heightened sensitivity to drought conditions due to mechanical constraints within their water transport systems. Conversely, soil fertility stands as a critical regulatory factor, particularly in nutrient-deficient conditions, when explaining discrepancies in forest biomass, growth rates, and stem turnover (Coomes et al. 2009). Consequently, favorable topographical conditions can directly enhance local soil fertility or light exposure, impacting the conditions for tree growth. This, in turn, has a bearing on forest diversity, structure, and the dynamics of biomass (Becknell and Powers 2014; Jucker et al. 2018). For instance, in the forests of southwestern Borneo, a positive correlation was observed between the abundance of emergent trees (> 120 cm diameter at breast height) and soil phosphorus levels as well as exchangeable bases (Paoli et al. 2008). The competition among trees tends to escalate with an increase in resource availability (Paquette & Messier 2011). This heightened competition may favor traits emphasizing acquisition (e.g., high specific leaf area) in fertile soil conditions, potentially leading to a lower rate of biomass accumulation (Prado-Junior et al. 2016).

Interestingly, the influence of large-sized trees on the relationships between diversity, structure, and biomass in forest ecosystems has not been thoroughly investigated (Ali et al. 2019; Ali et al. 2018; Paquette & Messier 2011; Poorter et al. 2017). Given their prominent position in the canopy, the largest trees may face heightened vulnerability compared to sub-canopy and understorey trees in the face of climate change. This heightened vulnerability arises from their direct exposure to fluctuations in solar radiation, wind intensity, temperature variability, and relative air humidity (Bennett et al. 2015; Laurance et al. 2000; Lindenmayer et al. 2012; Meakem et al. 2018; Nepstad et al. 2007; Thomas et al. 2013). Furthermore, the visibility of large trees from the sky makes them ideal subjects for monitoring forest responses to climate change through remote sensing (Asner et al. 2017; Bennett et al. 2015). Large trees constitute a disproportionate share of the total aboveground biomass (AGB) in tropical forests (Chave et al. 2001), but their relative contribution to the total AGB varies among tropical regions (Feldpausch et al. 2012).

Pakistan boasts a diverse geography and seasonal variation. The southwestern region, bordering the Arabian Sea in the northeast, is a mosaic of arid plateaus, stunning valleys, sandy deserts, and picturesque beaches. Moving towards the north, the landscape transforms into a blend of the Indus basin, mountain ranges, lush valleys, snow-capped peaks, and mangrove forests along the Arabian Sea. The northern areas showcase the grandeur of Pakistan, featuring the highest mountain ranges. These mountainous terrains cover a significant 60% of the country's landmass, mostly concentrated in the northern regions (Razaq 2012). Notably, Pakistan is home to the world's second-highest peak after Mount Everest, the formidable K2 in the Karakoram Range. Another iconic peak is Nanga Parbat, towering at 8126m, ranking as the second-highest peak in the Himalayas and situated in Pakistan. Additionally, there are smaller peaks like Kohi Suliman, Salt

Range, Kohi Kirtar, and the Mekran coast range along the western part of the country (Barry & Bishop 2012). The mountain ranges in Pakistan are distinct for their diverse vegetation and forests. For instance, the Kirthar range is home to tropical thorn forests, characterized by umbrella-shaped thorny vegetation where larger trees are less abundant. Dominant species in this region include *Prosopis glandulosa*, *Prosopis juliflora*, *Acacia modesta*, *Ziziphus nummularia*, *Salvadora oleoides*, and *Combretum molle* (Ali et al. 2023). Moving to the Kohi Suliman ranges, the world's largest old-age pure stand of *Pinus gerardiana* is found here, with some notable big trees boasting larger diameters due to distinct geological and topographic features. Spanning across the country, the Himalayas harbor a variety of vegetation. In the foothills of the lower Himalayas, one can find subtropical broad-leaved forests (Champion et al. 1968). Additionally, a significant portion of the country's mostly moist temperate forests is also situated within the Himalayas. The Himalayas stand out as one of the world's twenty-five biodiversity hotspots. The northern regions of Pakistan host primarily temperate forest types, notably in locations like Upper Dir, Lower Dir, Swat, Murree-Hazara Hills, and Kaghan valley. These forests, situated in inner valleys, reach their maximum height and diameter, resulting in a majority of sizable trees (Ali et al. 2023). In the Hindukush ranges, one can find dry temperate coniferous forests. These particular forests benefit from climatic and topographic conditions, allowing trees to grow to heights above 50 meters (Ali et al. 2023). The temperate forests primarily consist of gymnosperm trees like *Cedrus deodara*, *Abies pindrow*, *Pinus wallichiana*, and *Taxus wallichiana*. These gymnosperm-dominated forests often feature patches of broad-leaved trees mixed with conifers. Despite significant progress in understanding the global impact of large-diameter trees on aboveground biomass, a clear consensus regarding the significance of attributes related to big-sized trees in comparison to species diversity and other tree attributes on overall aboveground biomass at the community level in diverse natural forests at a large scale is lacking (Lutz et al. 2018). While the ecological importance of large-diameter trees within specific forest types is acknowledged, there remains a notable gap in our knowledge regarding the worldwide distribution and abundance of these large-diameter trees.

5.1.2 Hypothesis

It is hypothesized that big trees are found in diverse types of habitats and have a major role in determining aboveground biomass rather than medium and small trees in the natural forest ecosystem of Pakistan.

It is hypothesized that climatic and soil conditions play an important role in big tree stand structure and therefore enhance aboveground biomass.

It is hypothesized that big trees are also dependent on Shannon diversity (SD) and community waited traits mean (CWM) along with soil and climatic conditions.

5.1.2 Objective

To determine the role of big trees, medium trees, and small trees in the aboveground biomass in the natural forest ecosystem of Pakistan.

To find out the role of soil physiochemical properties and climatic-related factors in forest big trees medium trees and small trees in the natural forests of Pakistan.

To evaluate the role of CWM and Shannon diversity forest on big trees, medium trees, and small trees in the natural forest ecosystems of Pakistan.

5.1.3 Hypothetical model

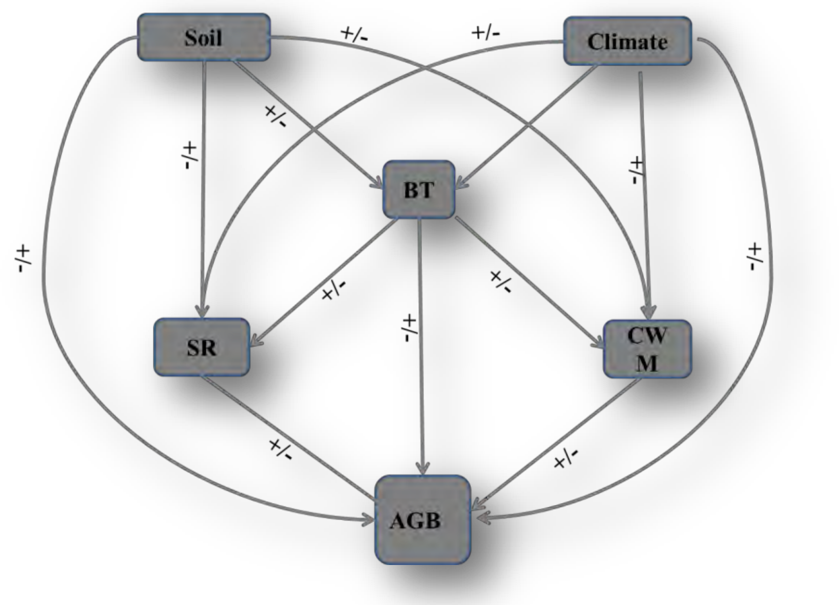


Figure 41 Hypothetical model explaining the effect of soil physicochemical properties, climate, on big trees (BT) community weighted mean (CWM), and species richness (SR) on aboveground biomass (AGB).

Variables with hypothesized relationships are denoted by -, +, or -/+, accordingly. **Abbreviations;** CWM= community weighted traits mean, SR= species richness, and AGB= aboveground biomass.

5.2 Methodology

For the current study, we collected data from a forest inventory (see *Chapter 2*). The data were categorized such big trees (diameter at breast height ≥ 50 cm), medium trees (diameter at breast height 25–50 cm), and small small trees (diameter at breast height – 25 cm). The data set includes biotic variables representing Shannon diversity (SD), and community-weighted traits mean (CWM). Abiotic variables include soil representing the soil clay loam percentage, soil carbon nitrogen phosphorus (CNP), other soil macro properties (SMP), such as cobalt, magnesium, calcium, sodium, and soil micro properties (SmP) such as chromium, nickel, copper, and manganese. limate represents the mean temperature, mean precipitation, relative humidity, and wind pressure.

5.2.1 Statistical analysis

To investigate the impact of climate, soil, big trees, medium trees, small trees, and SD on aboveground biomass, a structural equation model (SEM) was developed. The goodness of fit (GFI) was assessed using several statistical tests, such as the Chi-squared test, comparative fit index (CFI), standardized root mean square residual (SRMR), Bayesian information criterion (BIC), and Akaike's information criteria (AIC). To determine whether the data were multi-collinear, a variance inflation factor (VIF) test was performed. The VIF test has roughly 2.50 relevance in our case. Linear regression was employed to determine the complete path measurements of the structural equation modeling (SEM) results for each conceptual path (Figure 41). Scatter plots were used by employing the function plot (x, y) to investigate the relationship between aboveground biomass and structural diversity (SSD) in all strata such as big trees (BT), medium trees (MT), and small trees (ST). The linear models between y and x were fitted using the function lm (). All the analyses were done in R 3.6.3 (Ali et al. 2023).

5.3 Results

5.3.1 Effect of soil on community weighted traits mean (CWM) big trees, diversity, stand structure, and aboveground biomass

An increase in soil clay loam and carbon-nitrogen phosphorous (CNP) has a positive impact on big trees Shannon diversity, community-weighted trait mean (CWM), and aboveground biomass (AGB). Similarly, an increase in big trees (BT) and CWM also has a positive impact on AGB. While the increase in Shannon diversity (SD) has an adverse impact on AGB (Figure 42 A, Appendices 33 & 34). On the other side increase in soil micro properties leads to an increase in big trees, CWM, and aboveground biomass while an increase in macro properties (SMP) has an adverse impact on big trees (BT), CWM, SD, and AGB. Where an increase in BT also has a positive impact on CWM and AGB. Similarly, an increase in CWM has a positive impact on aboveground biomass productivity (Figure 42 B, Appendices 35 & 36).

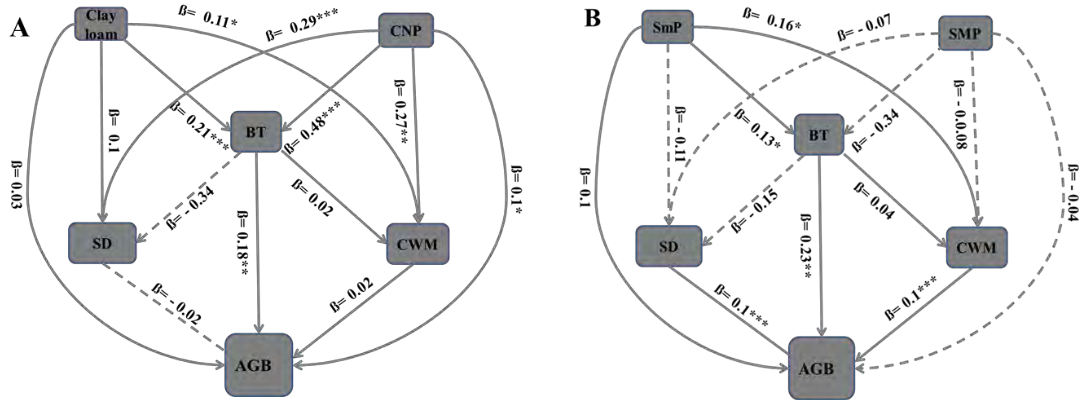


Figure 42 Impact of soil (i.e., soil micro properties (SmP), soil macro properties (SMP), clay loam, and carbon-nitrogen phosphorous (CNP), big trees (BT), Shannon diversity (SD), community weighted trait means (CWM) on aboveground biomass (AGB)

(A) Impact of clay loam, CNP, and BT, SD, CWM on AGB. (B) Impact of SmP, and SMP, BT, SD, and CWM on AGB. The stars represent the level of significance * > 0.05 **> 0.005 and *** represent >0.0005 respectively.

5.3.2 Effect of climate on community weighted traits mean, big trees, Shannon diversity, and aboveground biomass

An increase in mean precipitation (MP) has a positive impact on big trees (BT), community-weighted traits mean (CWM), Shannon diversity (SD), and aboveground biomass (AGB) while an increase in mean temperature (Mt) has a positive impact on Shannon diversity and AGB. Increase in temperature leads to a decline in big trees and CWM. An increase in BT and CWM also led to an increase in AGB (Figure 43A, Appendices37 & 38). On the other hand increase in mean relative humidity (MRH) and mean wind pressure (MWP) has an adverse impact on AGB while the increase in big trees and CWM has a positive impact on aboveground biomass productivity (Figure 43B, Appendices39 & 40).

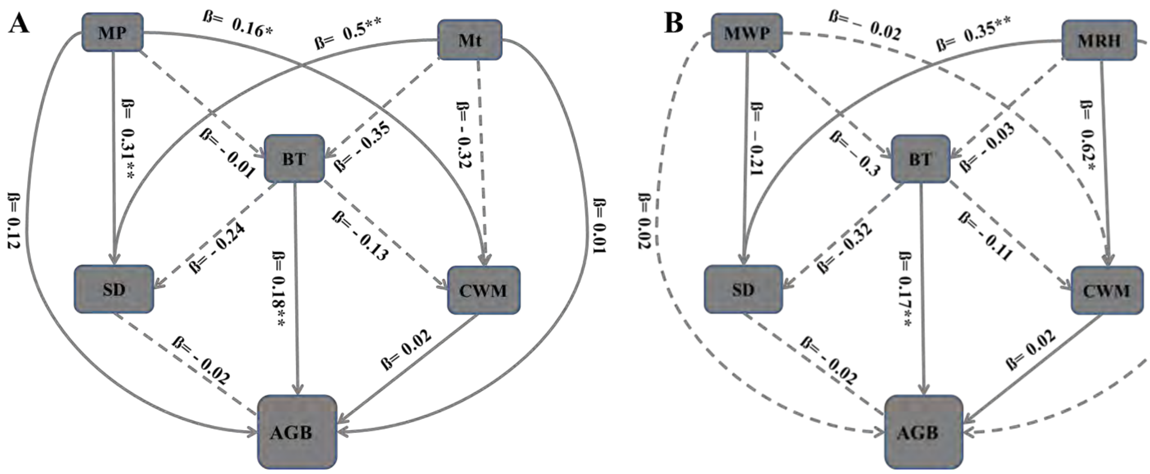


Figure 43 Impact of climate (i.e., mean precipitation (MP), mean temperature (Mt), mean wind pressure (MWP), and mean relative humidity (MRH), big trees (BT), Shannon diversity (SD), community-weighted traits mean (CWM) on aboveground biomass (AGB).

(A) Impact of MP, Mt, and big trees, SD, CWM on AGB. (B) Impact of MWP, and MRH, big trees, SD, CWM, and on AGB. The stars represent the level of significance * > 0.05 **> 0.005 and *** represent >0.0005 respectively.

5.3.3 Effect of soil on community weighted traits mean, big trees, medium trees, small trees, Shannon diversity, and aboveground biomass

An increase in soil clay loam concentration has a positive impact on big trees (BT), medium trees (MT), small trees (ST), community-weighted traits mean (CWM), Shannon diversity (SD), and aboveground biomass (AGB) while the increase in soil carbon nitrogen phosphorous (CNP) has a positive impact on CWM, SD, BT, MT. Similarly increase in BT, MT, and ST has a positive impact on AGB. While the increase in BT has an adverse impact on MT and ST respectively (Figure 44 A, Appendices41 & 42). On the other side increase in soil micro properties (SmP) has a positive impact on BT, MT, CWM, and aboveground biomass. An increase in soil macro properties (SMP) has a positive impact on ST and AGB. Similarly, an increase in BT also has a positive impact on CWM and AGB while an adverse effect occurs in medium and small trees. An increase in medium and small trees also has a positive impact on AGB. Moreover, a decrease in CWM and SD has an adverse effect on aboveground biomass productivity (Figure 44 B, Appendices43 & 44).

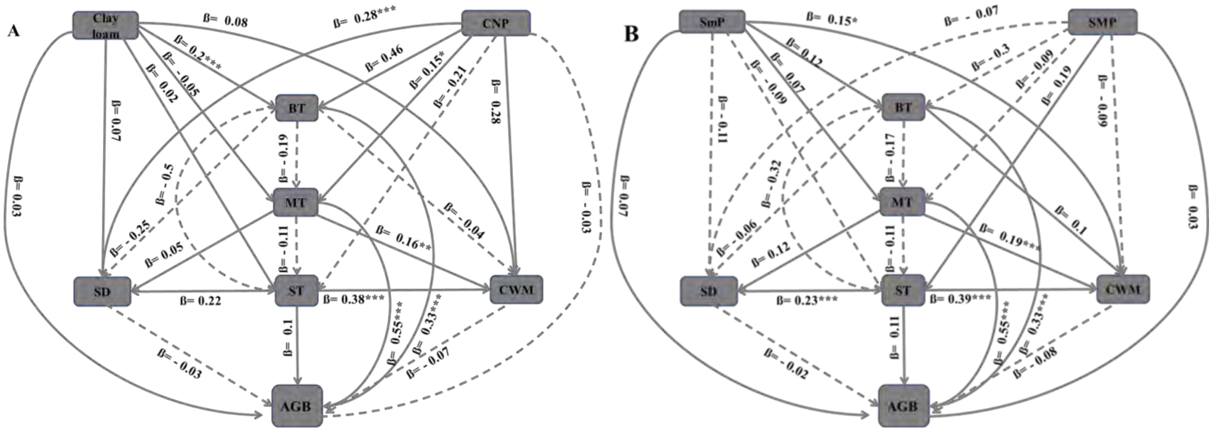


Figure 44 Impact of soil (i.e., soil clay loam, carbon-nitrogen phosphorous (CNP), soil micro properties (SmP), and soil macro properties (SMP), big trees (BT), medium trees (MT), small trees (ST), Shannon diversity (SD), community weighted traits mean (CWM) on aboveground biomass (AGB).

(A) Impact of clay loam, CNP, BT, MT, ST, SD, CWM on AGB. (B) Impact of SmP, and SMP, BT, MT, ST, SD, CWM, and on AGB. The stars represent the level of significance * > 0.05 **> 0.005 and *** represent >0.0005 respectively.

5.3.4 Effect of climate on community weighted traits mean, big trees, medium trees, small trees, diversity, stand structure, and aboveground biomass

An increase in mean precipitation (MP) has a positive effect on big trees (BT), small trees (ST), community-weighted traits mean (CWM), Shannon diversity (SD), and aboveground biomass (AGB). While the increase in mean temperature (Mt) also has a positive effect on ST, SD, and AGB. An increase in BT has a positive effect on AGB while an adverse effect on MT and ST. Similarly, an increase in CWM also has a positive effect on AGB (Figure 45A, Appendices 45 & 46). On the other side increase in mean wind pressure (MWP) has a positive effect on MT while an adverse effect on BT, ST, SD, CWM, and AGB. Similarly increase in BT, MT, and ST has a positive effect on AGB. However, the increase in mean relative humidity (MRH) also has a positive effect on BT, MT, ST, SD, and CWM. Furthermore, an increase in BT, MT, ST, and CWM also has a positive effect on aboveground biomass productivity (Figure 45B, Appendices 47 & 48).

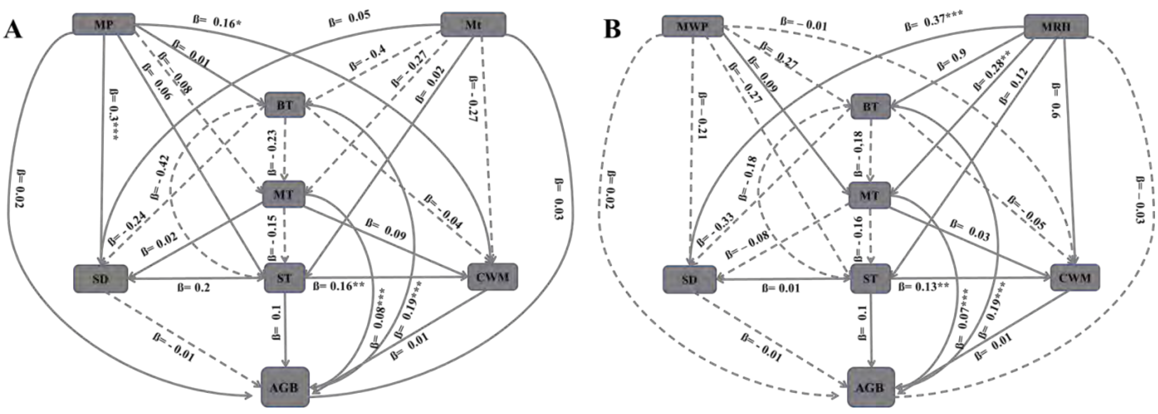


Figure 45 Impact of climate (_i.e.‘ mean precipitation (MP), mean temperature (Mt), mean wind pressure (MWP), and mean relative humidity (MRH), big trees (BT), medium trees (MT), small trees (ST), Shannon diversity (SD), community weighted traits mean (CWM) on aboveground biomass (AGB)

(A) Impact of MP, Mt, and BT, MT, ST, SD, CWM on AGB (B) Impact of MWP, and MRH, BT, MT, ST, SD, and CWM on AGB. The stars represent the level of significance * > 0.05 **> 0.005 and *** represent >0.0005 respectively.

5.3.5 The relationship between biotic determinants and aboveground biomass

An increase in specific leaf area, mean leaf area and wood density leads to an increase in above-ground biomass. While the increase in leaf thickness and leaf dry matter content leads to a decline in aboveground biomass productivity (Figure 46). A decline was noted in aboveground biomass productivity with an increase in small tree stand structure diversity (Figure 47). Aboveground biomass significantly increases with an increase in medium tree stand structure diversity except the medium tree species richness which leads to a decline in aboveground biomass productivity (Figure 48). Aboveground biomass significantly increases with an increase in big tree stand structure diversity (Figure 49).

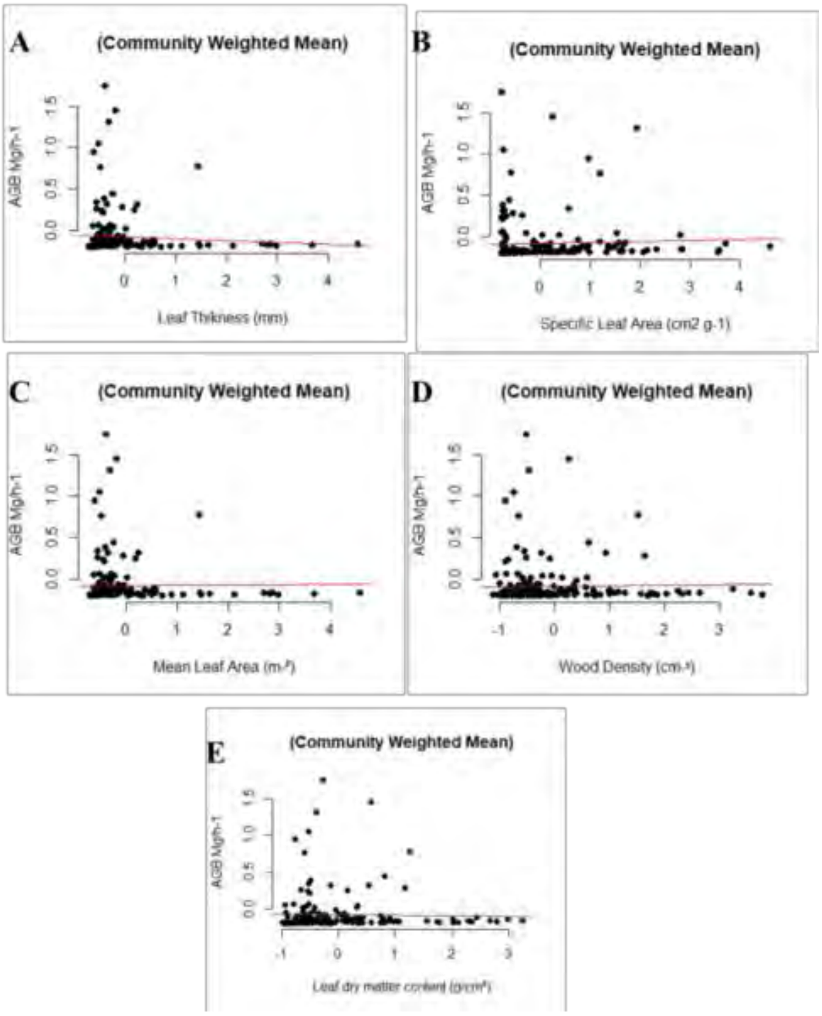


Figure 46 Relationship between community weighted traits mean (CWM) and aboveground biomass.

(A) Relationship between leaf thickness and aboveground biomass. (B) Relationship between specific leaf area and aboveground biomass. (C) Relationship between mean leaf area and aboveground biomass. (D) Relationship between wood density and aboveground biomass. (E) Relationship between leaf dry matter content and aboveground biomass.

5.3.6 The relationship between small tree stand structure diversity and aboveground biomass

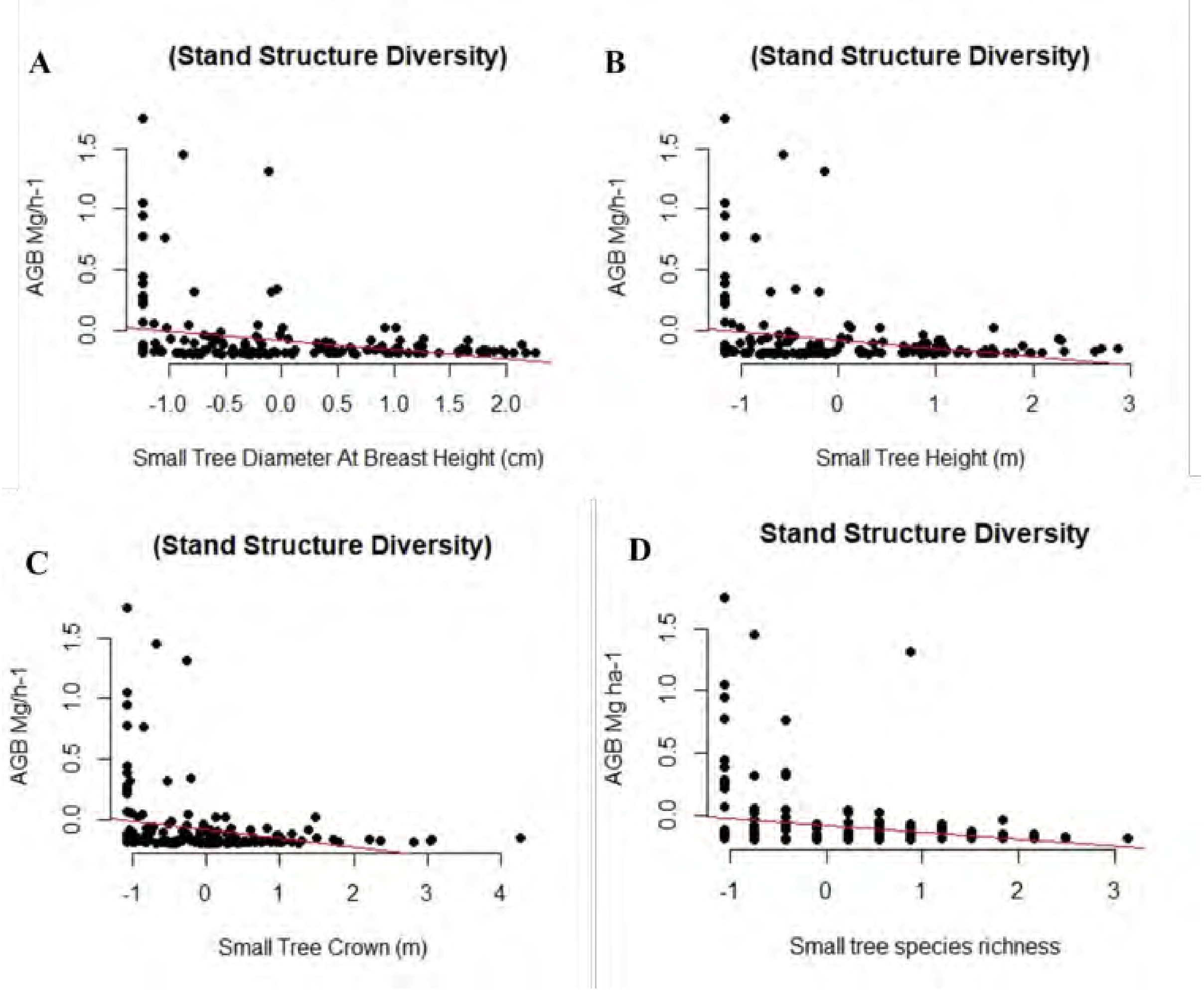


Figure 47 Relationship between small tree stand structure diversity and aboveground biomass.

(A) Relationship between small tree diameter at breast height and aboveground biomass. (B) Relationship between small trees height and aboveground biomass. (C) Relationship between small trees crown and aboveground biomass. (D) Relationship between small trees species richness and aboveground biomass.

5.3.7 The relationship between medium tree stand structure diversity and aboveground biomass

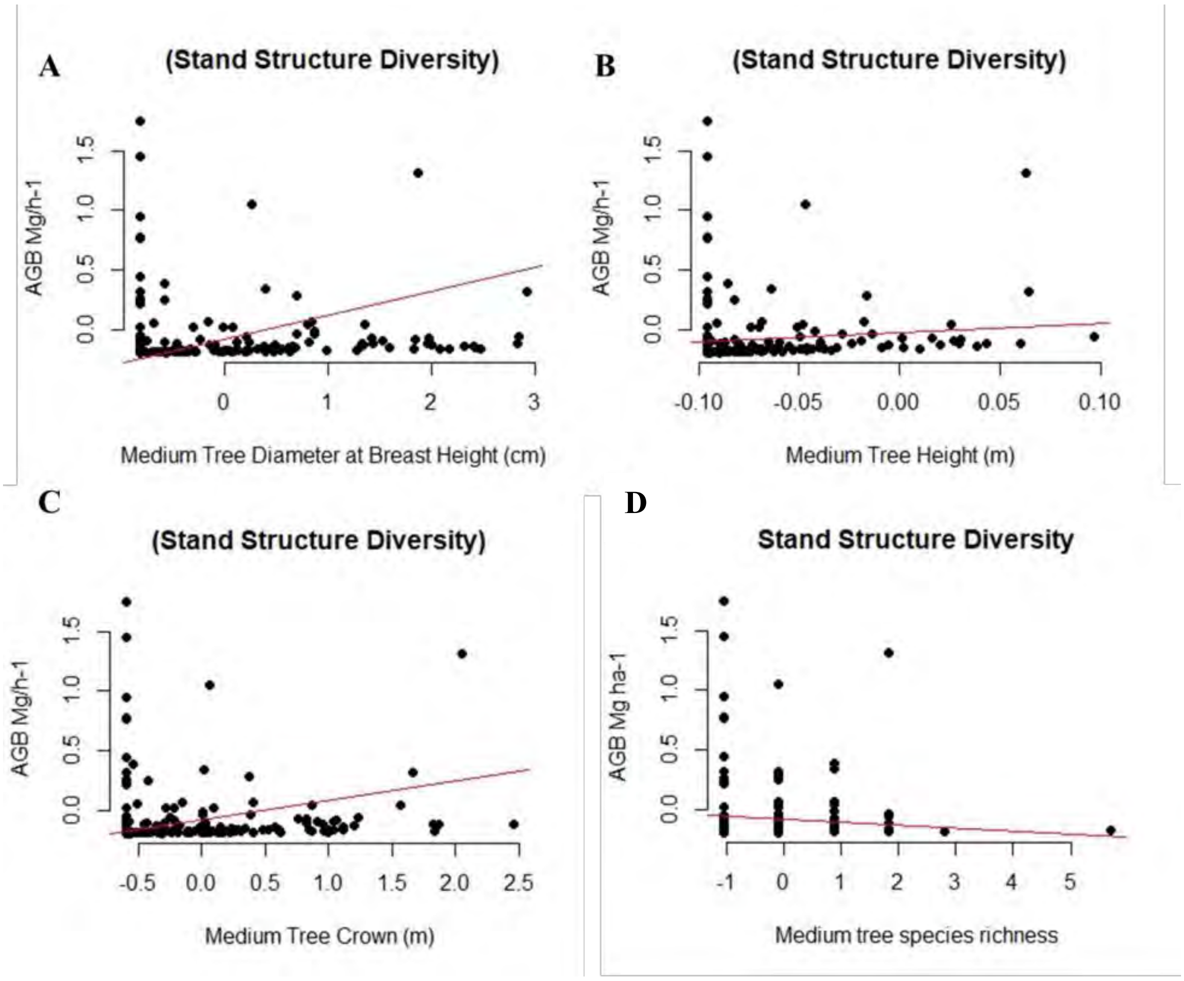


Figure 8 Relationship between medium trees stands structure diversity and aboveground biomass. (A) Relationship between medium tree diameter at breast height and aboveground biomass. (B) Relationship between medium tree height and aboveground biomass. (C) Relationship between medium trees crown and aboveground biomass. (D) Relationship between medium tree species richness and aboveground biomass.

5.3.8 The relationship between big tree stand structure diversity and aboveground biomass

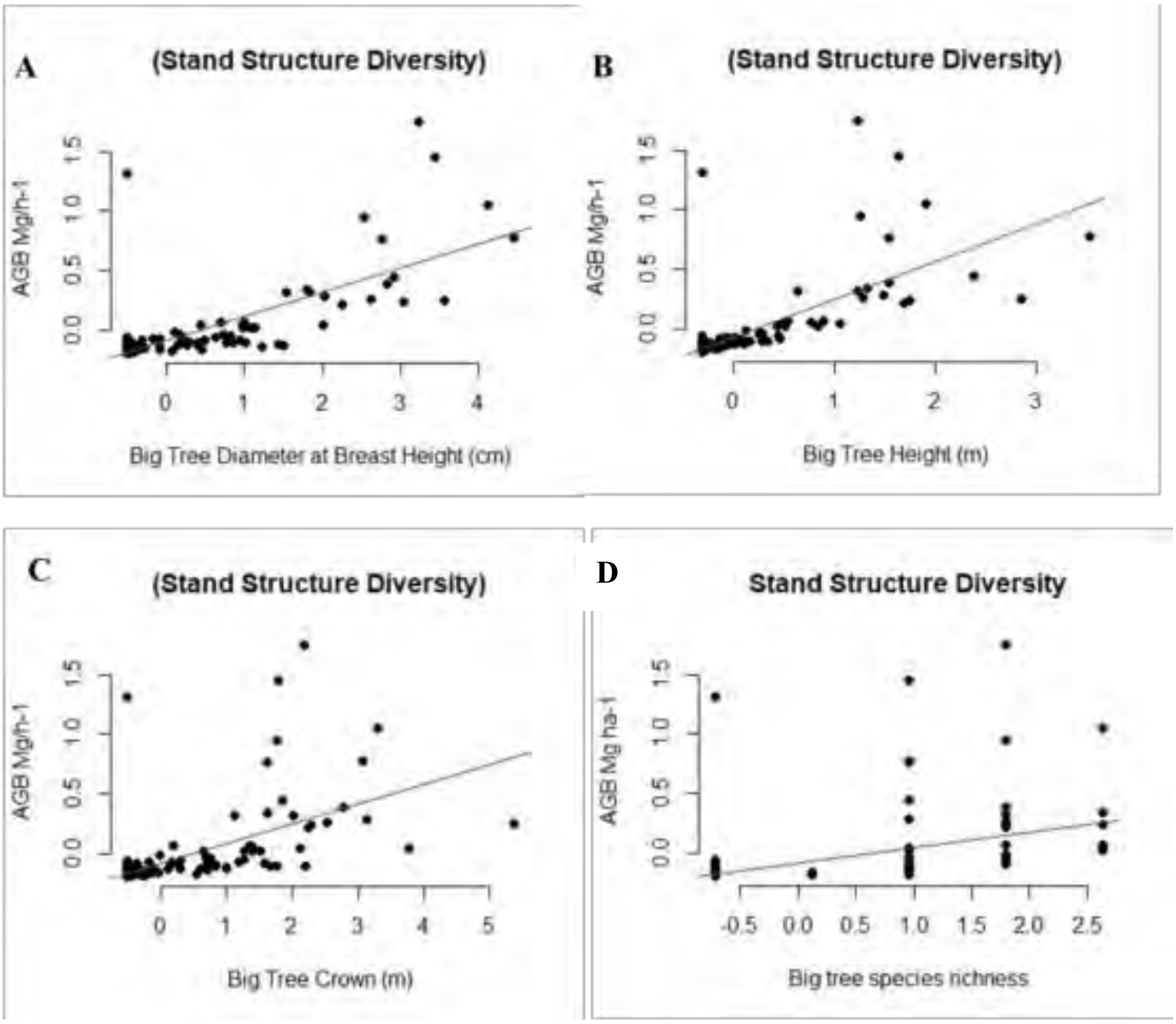


Figure 48 Relationship between big trees, stand structure, diversity, and aboveground biomass.

(A) Relationship between big trees diameter at breast height and aboveground biomass. (B) Relationship between big tree height and aboveground biomass. (C) Relationship between big trees crown and aboveground biomass. (D) Relationship between big tree species richness and aboveground biomass.

5.3.9 The relationship between species diversity and aboveground biomass

Species diversity leads to a decline in aboveground biomass productivity (Figure 49).

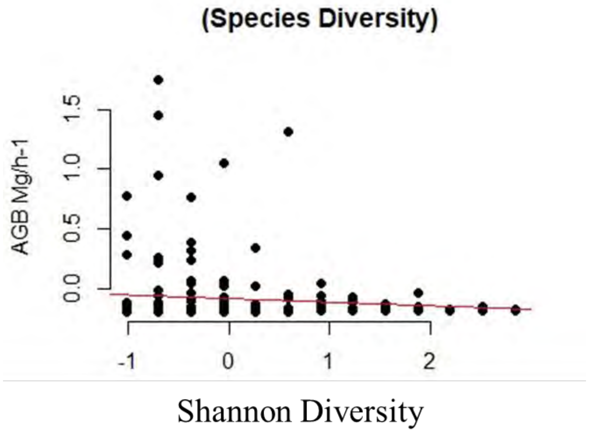


Figure 49 The relationship between species diversity and aboveground biomass.

5.3.10 Overall relationship of biotic and abiotic variables of aboveground biomass

Medium trees, big trees, climate CWM, and Shannon diversity are mainly determined by aboveground biomass (Figure 11).

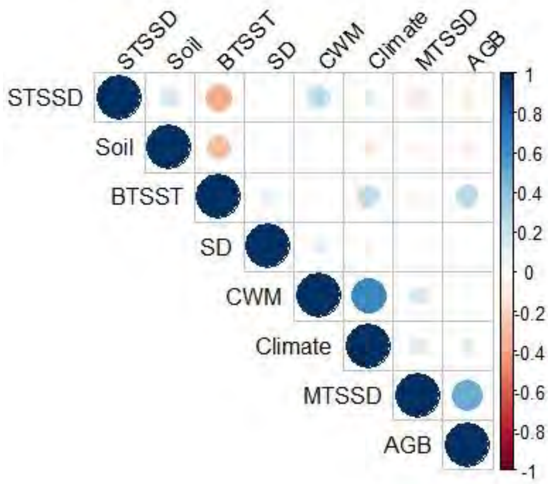


Figure 50 The relationship between biotic and abiotic variables of aboveground biomass.

5.4 Discussion

In this study, we evaluated the role of big trees (DBH greater than 75 cm), and their impact on the remaining trees, i.e., medium and small trees along with their biotic and abiotic determinants on aboveground biomass in different forest types. We found that an increase in soil fertility leads to an increase in the big trees and enhances aboveground biomass productivity. Similarly, an increase in temperature and precipitation also leads to enhanced aboveground biomass productivity while an increase in relative humidity and wind pressure leads to a decline in big trees. We found in our study that there is a low concentration of big trees in sub-tropical thorn, sub-tropical broad-leaved forests, dry temperate *Quercus* forests, and dry temperate pure *Pinus gerardiana* forests. These forests are found on nutrient-deficit sites and are exposed to numerous environmental factors that limit the growth of large-diameter trees. The majority of aboveground biomass is found in the understory and sub-canopy trees. In these forests, aboveground biomass dependens on soil-related factors. In the current study, the big trees were mainly found in moist temperate mixed forests and dry temperate conifer forests. These forests were found in the inner valleys of the Himalayas and the Hindu Kush Mountains and were protected from wind storms and other natural and anthropogenic disturbances. The trees in these forests reach several hundred cm of DBH and also reach above 50 meters in height. In these forests especially in the dry temperate forest, the understory and sub-canopy vegetation is rare because of the acquisitive strategy and limits the available resources for remaining trees. Our findings align with earlier research, underlining the pivotal role of soil fertility in elucidating variations in forest biomass, growth, and stem turnover rates, particularly in nutrient-deficient conditions (Baker et al. 2009; Coomes et al. 2009). Favorable topographical conditions play a direct role in enhancing local soil fertility or light conditions conducive to tree growth. This, in turn, influences forest diversity, structure, and the dynamics of biomass (Becknell & Powers, 2014; Jucker et al., 2018). A case in point is the positive correlation observed between the abundance of emergent trees (>120 cm diameter at breast height) and soil phosphorus as well as exchangeable bases in southwestern Borneo forests (Paoli et al. 2008). In our studies, the big trees were also extremely sensitive to climatic conditions in sub-tropical thorn, sub-tropical broad-leaved forests, dry temperate *Quercus* forests, and dry temperate pure *P. gerardiana* forests. These forests were found on harsh climatic sites and were exposed to numerous environmental factors that limit the growth of large-diameter trees and majorly the sub-canopy trees contribute to aboveground biomass. In these forests, higher wind pressures were reported which was one of the key factors limiting the growth of large trees. The majority of big trees were found in the inner valleys and their presence was strongly correlated with topographic and climatic factors. Our observations align with earlier research highlighting that large-diameter trees take several decades or even centuries to reach maturity and occupy the forest canopy. These trees were notably more susceptible to global environmental shifts compared to understorey and sub-canopy trees, given their direct exposure to relative air humidity, solar radiation, wind strength, and temperature fluctuations (Bennett et al. 2015). In the current study, we found that big trees had an important role in aboveground biomass productivity but they also lead to a decline in the remaining trees or sub-canopy because big size of trees limit the available resources for remaining trees and hence control the understory vegetation (Ali et al. 2018; Messier et al. 1998; Yuan et al. 2012). In this study, we found that big trees are abundant in dry temperate conifer and moist temperate mixed forests and have a strong positive impact on aboveground biomass rather than remaining trees. These findings are consistent with prior research. The substantial positive impact of large-sized trees on aboveground biomass implies that forests can sequester significant amounts of aboveground carbon, particularly when they harbor large-diameter trees with tall stature and expansive crowns. This holds irrespective of the species richness and composition of the remaining trees within the forest (Bastin et al. 2018; Feldpausch et al. 2012; Lutz et al. 2018; Slik et al. 2013; Stephenson et al. 2014). In the current study, we notice the big size trees are not abundantly found in the sub-tropical thorn, sub-tropical broad-leaved, dry temperate pure *P. gerardiana,* and dry temperate *Quercus* forest and the aboveground biomass is determined by the remaining or sub-canopy-vegetation. We found that the CWM of big trees enhances aboveground biomass and this enhancement is regulated by soil fertility-related factors. However, these phenomena were recorded as strongly significant in the remaining trees. Our findings align with previous research indicating that the understorey stratum primarily hosts slow-growing plant species, leading to a positive feedback loop with Community-Weighted Mean (CWM) and resulting in higher aboveground biomass (Ali & Yan 2017). Moreover, we observe a decrease in aboveground biomass in natural forest ecosystems corresponding to higher Shannon diversity, consistent with earlier studies. The direct negative impact of Shannon's species diversity on aboveground biomass suggests that an abundance of biomass in the understorey may outcompete weaker competitors, aligning with the concept of competitive exclusion (Ali et al. 2016). Consequently, the dominance of specific productive species employing particular strategies significantly influences aboveground biomass (Prado-Junior et al. 2016; Ali & Yan 2017). Taxonomic diversity enhanced aboveground biomass in forests with large trees, a finding that is in line with previous research. However, it is noteworthy that aboveground biomass may indeed increase with taxonomic diversity (Zhang et al. 2012). The current study suggests that big trees are only found in topographically isolated and fertile habitats because big trees take centuries to reach the highest threshold and play a crucial role in aboveground biomass productivity. Overall in the Pakistani forest medium and small trees contributed more than big trees because most of the forests are situated in areas where the climatic and soil conditions are harsh which leads to a decline in big trees.

5.5 Conclusion

We conclude that climatic and soil conditions play a crucial role for big trees and therefore contribute to aboveground biomass productivity but they also lead to a decline in remaining trees. Some of the forests which are topographically isolated and protected from natural as well as human disturbance host the majority of the big trees but they also limit the growth of the remaining trees. Overall it is concluded that the majority of aboveground biomass is present in the medium and small trees rather than the big trees and big trees have adverse effects on the remaining trees which leads to a decline in aboveground biomass productivity.

Multiple biotic and abiotic drivers of aboveground biomass (AGB)

Introduction

Forests, as vital ecosystems, offer a multitude of ecological, social, and economic benefits. The measurement of aboveground biomass (AGB) in forests is important for assessing forest productivity and carbon storage. Determinants of AGB in forest ecosystems are intricate and multifaceted, with both biotic and abiotic factors playing pivotal roles. Biotic factors influencing AGB in forest ecosystems include species composition, stand density, and plant competition. In contrast, abiotic factors, including climatic variables like temperature, precipitation, and soil nutrient availability, are also influential. Comprehending the relative significance of these drivers is essential for anticipating variations in forest productivity and carbon storage under diverse scenarios, such as those shaped by climate change or forest management practices (Clark 2016). Numerous investigations have explored determinants of aboveground biomass (AGB) in forest ecosystems, and the outcomes have exhibited variations contingent on factors like the research location, forest type, and the adopted methodologies. For instance, in their study, Lai and collaborators (2019) ascertained that in a tropical rainforest in China, species composition stood out as the foremost influencer of AGB. Conversely, Coomes and collaborators (2016) established that stand density took precedence as the most crucial factor affecting AGB in a beech forest in New Zealand. Additionally, some studies have underscored the pivotal role of abiotic factors, including temperature and precipitation. In this regard, the research by Clark and collaborators (2016) identified temperature as the primary driver of AGB in a boreal forest in Alaska, while Zhang and collaborators (2016) determined that precipitation was the primary AGB driver in a temperate forest in China.

Within forest ecosystems, variations in factors such as the number of species, functional traits, and tree sizes, in conjunction with abiotic elements, collectively determine aboveground biomass and overall productivity (Paquette et al. 2015; Prado-Junior et al. 2016). Presently, research has elucidated the concurrent impacts of several abiotic factors, like soil nutrients, and biotic factors, including biodiversity and stand structure, on the functioning of whole forest communities (Fotis & Curtis 2017; van der Sande et al. 2017). Despite the inherent presence of auto-correlated spatial structures that complicate many analyses, it has been observed that forest structure and dynamics are significantly and quantitatively linked to both edaphic and climatic conditions. Basin-wide disparities in turnover rates at the stand level are predominantly shaped by soil physical properties, with variations in coarse wood production rates primarily associated with soil phosphorus status. A role for soil potassium in modulating Amazon forest dynamics through its effects on stand-level wood density was also detected. Taking this into account, otherwise enigmatic variations in stand-level biomass across the Amazon were then accounted for through the interacting effects of soil physical and chemical properties with climate. Stand-to-stand variation in Amazon forest structure and dynamics at a basin-wide scale can potentially be due to three interacting factors. First, tropical tree taxa are not distributed randomly across the Amazon basin but rather show spatial patterning attributable to both biogeographic and edaphic/climatic effects. Included in the former category are differences between different taxa in their geographical origins and subsequent rates of diversification and dispersion (Richardson et al. 2001) with these phenomena then potentially interacting with the second factor, viz. a tendency for particular taxa to associate with certain soils and/or climatic regimes (Honorio Coronado et al. 2009; Toledo et al. 2011a).

An influence of soil potassium on the modulation of Amazon forest dynamics, particularly through its impact on wood density at the stand level, has been established. By considering this, what were previously puzzling variations in stand-level biomass across the Amazon basin have been elucidated by accounting for the interactive effects of soil physical and chemical properties with climate. The variations in Amazon forest structure and dynamics from one stand to another on a basin-wide scale can potentially be attributed to the interplay of three factors. Firstly, the distribution of tropical tree taxa in the Amazon Basin is not random but exhibits spatial patterns that can be attributed to both biogeographic and edaphic/climatic effects. Within the realm of biogeography, differences among various taxa in terms of their geographical origins and subsequent rates of diversification and dispersion (Richardson et al. 2001) are noteworthy. These factors may then potentially interact with the second factor, namely, a propensity for certain taxa to be associated with specific soil and/or climatic conditions (Honorio Coronado et al. 2009; Toledo et al. 2011a). It is also possible that soils and climate have direct impacts on forest dynamics that are independent of species composition or associations, giving rise to a third component of variation, which is purely environmental. For instance, long-term fertilization trials have suggested that trees tend to grow faster in the presence of abundant essential nutrients (Wright et al. 2011). Similarly, research from long-term experiments simulating soil water deficits indicates that under less favorable precipitation conditions, stand-level growth rates are reduced. Furthermore, these factors are superimposed and underpinned by large-scale spatial patterns in the potential environmental drivers of forest structure and dynamics. For instance, temperature, precipitation, and soil type exhibit non-random variations across the Amazon basin (Malhi & Wright 2004; Quesada et al. 2011).

In forest ecosystems, there is a positive correlation between functional trait diversity and both phylogenetic and taxonomic diversity. This relationship arises from traits converging among species that are phylogenetically dissimilar or diverging among phylogenetically similar species (Wiens & Graham 2005; de Bello 2012). However, when it comes to their impact on aboveground biomass, factors like phylogenetic diversity, species richness, evenness, clustering, and variability at the tips of phylogeny in a species-rich community can have varying effects (Ali & Yan 2018). Additionally, the mass ratio hypothesis (Grime 1998) posits that aboveground biomass should be strongly associated, either positively or negatively, with the community-weighted mean (CWM) of trait values, which represents functional identity or trait composition. This is because it is the dominant trait value, not the diversity of traits that primarily influences aboveground biomass (Prado-Junior et al. 2016; Fotis et al. 2017). Traits related to plant growth rate and resource re-acquisition are expected to play a mechanistically significant role in determining high aboveground biomass or productivity (Garnier et al. 2004; Finegan et al. 2015). However, the relationship between functional identity and aboveground biomass or productivity can exhibit different patterns and magnitudes in various forest types. For example, conservative traits that enhance drought tolerance, such as dense wood and lower specific leaf area, tend to promote aboveground biomass productivity in tropical dry forests (Prado-Junior et al. 2016). In contrast, these same conservative traits can constrain aboveground biomass or productivity in tropical wet and moist forests (Malhi et al. 2004; Finegan et al. 2015). In contrast to tropical forests, both conservative and acquisitive traits play a role in promoting aboveground biomass in subtropical forests (Chiang et al. 2016; Lin et al. 2016; Ali et al. 2017). Furthermore, in sub-tropical forests, aboveground biomass and productivity are more strongly influenced by functional dominance, which represents the community-weighted mean (CWM) of plant maximum height or diameter, as opposed to the CWM of leaf traits (Prado-Junior et al. 2016; Ali & Yan 2017b). Aboveground biomass is not solely determined by biodiversity aspects but also by the structural complexity of the forest stand, including factors like individual tree size variation, tree diameter, height diversity, stand-level tree mean diameter, stand basal area, and stand density (Poorter et al. 2015; Fotis et al. 2017). Consequently, both species diversity and stand structural complexity can impact aboveground biomass through feedback mechanisms or interactions. For instance, species diversity indirectly contributes to aboveground biomass by influencing tree diameter and height diversity within forest stands (Zhang & Chen 2015; Ali et al. 2016). The presence of trees with substantial diameters and maximum heights is significantly associated with higher aboveground biomass (Chiang et al. 2016; Ali & Yan 2017). The vertical stratification of forests affects light capture and utilization by plants, thereby shaping patterns of species diversity, functional diversity, and aboveground biomass between the overstorey and understorey strata. Light availability is more abundant in the overstorey stratum than it is in the understorey. However, the overstorey stratum limits the availability of light to the understorey due to competitive constraints in natural forests (Bartels & Chen 2010; Zhang et al. 2017). Consequently, understorey species may adopt either complementarity or conservative strategies, while functional dominance (in terms of adult stature) is more pronounced in the overstorey, playing a significant role in structuring aboveground biomass (Bartels & Chen 2010; Ali & Yan 2017b).

Moreover, local abiotic factors have both direct and indirect effects on aboveground biomass in natural forests (Poorter et al. 2015; Zhang & Chen 2015; Chiang et al. 2016). For example, the variation in light capture by different plant species can be influenced by topographic heterogeneity, diversity, functional identity, and the structural complexity of overstorey trees (Yuan et al. 2012; Ali and Yan 2017b). Simultaneously, according to the soil fertility hypothesis, soil physicochemical properties can strongly impact plant growth, thereby influencing species diversity, functional identity, stand structure, and aboveground biomass across different forest strata (Ali & Yan 2017b). Therefore, the potential drivers of biotic factors and aboveground biomass in both overstorey and understorey can be attributed to abiotic factors, such as soil physicochemical properties and climatic conditions.

Pakistan experiences a wide range of climatic conditions and seasonal variations, with changing factors such as its latitudinal position and elevation which play a significant role in driving climate differences and local vegetation variation. Pakistan spans approximately 23° to 37° parallel lines, covering numerous latitudinal regions despite its relatively compact size, and it rises from sea level (0 meters) in Karachi to the towering peak of K2, which stands at 8611 meters above sea level. Intermountain valleys and plains are enriched with alluvial soil from rivers originating in the higher mountain ranges. Notably, Pakistan is home to distinct plateaus such as the Potohar, Baluchistan, and the Deosai (the second largest in the world after the Tibetan plateau), each characterized by unique species compositions and climatic conditions. Therefore, the variation in latitudes and elevations across the country contributes to the diverse local climates. Pakistan enjoys all four seasons throughout the year, and the summer monsoon rains occur from July to September (Khan 2020). The extensive mountain ranges within the country cover about 61% of its total land area (Rasul & Hussain 2015). These mountain ranges significantly influence the prevailing environmental conditions, in part due to Pakistan's northern location, which is at the convergence of three renowned mountain ranges: the Himalayas, Karakoram, and the Hindu Kush. These mountain ranges are home to the third-largest mass of ice in the world, following only the

Polar Regions. Pakistan's territory hosts more than 5000 glaciers, which, with their frozen reserves, play a crucial role in sustaining water supplies through the melting process. Pakistan's diverse geography also encompasses several deserts, including the Thar Desert in Sindh, the Cholistan Desert in the southeast of the Punjab Province, the Thar Desert in central Punjab, and the Kharan Desert in Baluchistan. Each of these supports unique species of organisms. The mountain ranges in the northern regions of Pakistan give rise to a comprehensive network of rivers, primarily due to the extensive glacier coverage in these areas. These rivers flow throughout the country, contributing to the diversity of species and the manipulation of the climate (Bajracharya & Shrestha, 2011).

In Pakistan, different types of forest include sub-tropical thorn forest, sub-tropical broadleaved forest, moist temperate mixed forest, dry temperate conifer forest, dry temperate *Quercus* forest, and dry temperate *P. gerardiana* forest. These forests were not previously discovered for the effect of multiple biotic and abiotic drivers of aboveground biomass. The objective of the current study was to evaluate the relative effects of abiotic and biotic drivers on aboveground biomass across overstorey and understorey, as well as at the whole community level in different forest ecosystems across Pakistan. Specifically, we asked the following research question; what is the relative effect of biotic drivers (stand structure diversity, community weighted traits mean, and Shannon diversity) and abiotic variables (i.e., soil clay loam, carbon nitrogen phosphorous (CNP), macro properties (SMP), and soil micro properties (SmP)) on aboveground biomass of the whole community, overstorey, and understorey across different forest types of Pakistan? In our theoretical framework, we propose that several factors contribute positively to the overall aboveground biomass within the community. These factors include Shannon diversity, community-weighted traits mean, stand structure diversity, and the presence of large trees, all of which are expected to exert a favorable influence on the whole community, overstorey, and understory aboveground biomass. Concurrently, we hypothesize that specific soil attributes play a crucial role in enhancing aboveground biomass productivity. Among these attributes are a clay loam-dominated composition and an abundance of carbon, nitrogen, phosphorous, and various micronutrients, excluding macronutrients. Additionally, we anticipate that precipitation, rather than factors such as temperature, wind pressure, and relative humidity, serves as a primary driver for the heightened productivity observed in aboveground biomass. Soil macronutrients, wind pressure, and relative humidity reduce aboveground biomass productivity in the whole community, overstorey, and understorey stratum.

6.1.1 Hypothetical Model

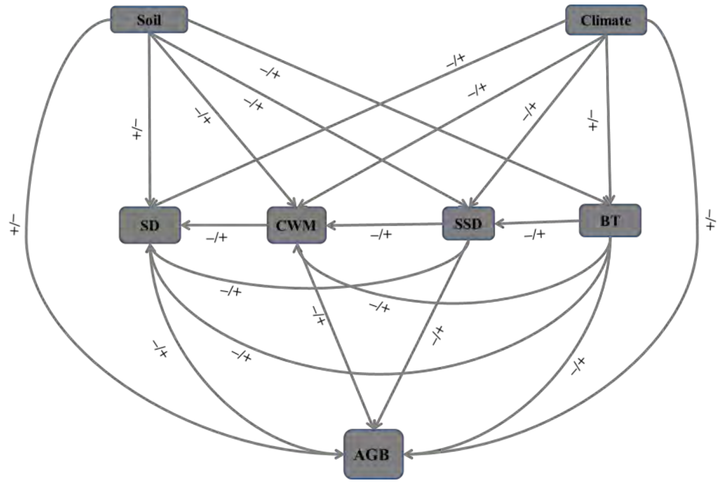


Figure 51 Hypothetical model explaining the effect of soil, climate, Shannon diversity (SD), community weighted mean (CWM), stand structure diversity (SSD), and big trees (BT) on aboveground biomass (AGB).

Variables with hypothesized relationships are denoted by -, +, or -/+, accordingly.

6.2 Methodology

For the current study, we collected data from a forest inventory (see *Chapter 2*). The data were categorized as overstorey, understorey, and whole community. The dataset includes biotic variables such as Shannon diversity (SD), community-weighted traits mean (CWM), stand structure diversity (SSD), big trees (BT), and aboveground biomass (AGB). The abiotic variables were represented by soil physicochemical properties such as soil clay loam, carbon-nitrogen-phosphorous (CNP), other soil macronutrients (SMP) i.e., cobalt, magnesium, calcium, sodium, and soil micronutrients (SmP) i.e., chromium, nickel, copper, and manganese. The climate represents the mean temperature (Mt), mean precipitation (MP), relative humidity (MRH), and wind pressure (MWP).

6.2.1 Statistical Analysis

To investigate the impact of multiple biotic such as Shannon diversity (SD), community-weighted traits mean (CWM), stand structure diversity (SSD), big trees (BT), and abiotic such as soil physicochemical properties such as soil and climate on aboveground biomass several structural equation models (SEM) were developed. The goodness of fit (GFI) was assessed using several statistical tests, such as the Chi-squared test, comparative fit index (CFI), standardized root mean square residual (SRMR), Bayesian information criterion (BIC), and Akaike's information criteria (AIC). To determine whether the data were multi-collinear, a variance inflation factor (VIF) test was performed. The VIF test has roughly 2.50 relevance in our case. Linear regression was employed to determine the complete path measurements of the structural equation modeling (SEM) results for each conceptual path (Figure 51). Scatter plots were used by employing the function plot (x, y) to investigate the relationship between aboveground biomass and structural diversity. The linear models between y and x were fitted using the function lm (). All the analyses were done in R 3.6.3 (Ali et al. 2023).

6.3 Results

6.3.1 The effect of soil and multiple biotic drivers of aboveground biomass in the whole community

Soil dominated with clay loam and rich in organic carbon, nitrogen, and phosphorus has a positive effect on the biotic drivers, i.e., Shannon diversity (SD), community-weighted traits mean (CWM), stand structure diversity (SSD), and big trees (BT) of the whole community, and enhanced aboveground biomass productivity (Figure 52A, Appendices49 & 50). On the other side soil macronutrients (SMP) also increased the biotic detriments of the whole community and enhanced the aboveground biomass productivity, while soil micronutrient also has an adverse effect on the biotic determinant of the whole community and therefore harmful effect on aboveground biomass productivity (Figure 52B, Appendices 51 & 52).

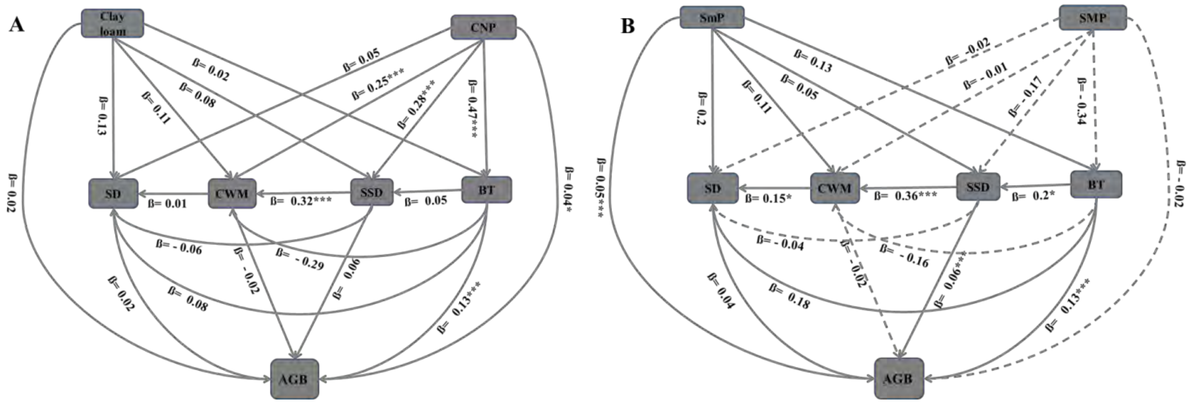


Figure 52 Impact of soil (i.e. soil clay loam, soil carbon nitrogen phosphorous (CNP), soil micro properties (SmP), and soil macro properties (SMP), Shannon diversity (SD), community weighted trait mean (CWM), stand structure diversity (SSD), big tree (BT) on aboveground biomass (AGB**).**

(A) Impact of Clay loam, CNP, SD, CWM, SSD, and BT on AGB. (B) Impact of SmP, and SMP, SD, CWM, SSD, and BT on AGB. The stars represent the level of significance * > 0.05 **> 0.005 and *** represent >0.0005 respectively.

6.3.2 Effect of climate on multiple biotic drivers of aboveground biomass in the whole community

An increase in mean precipitation (MP) has a positive effect on the biotic drivers, i.e., Shannon diversity (SD), community-weighted traits mean (CWM), big trees (BT) of the whole community, and enhanced productivity. An increase in mean temperature (Mt) also has a positive effect on the biotic determinants, i.e., Shannon diversity (SD), of the whole community, and enhanced productivity (Figure 53A, Appendices53 & 54). On the other hand, mean wind pressure (MWP) has led to a decline in the biotic detriments of the whole community and a decline in the aboveground biomass productivity. An increase in relative humidity leads to a decline in aboveground biomass productivity but they increase the biotic determinant, i.e., Shannon diversity, community-weighted traits mean, big trees, and stand structure diversity of the whole community and in turn increase aboveground biomass productivity (Figure 53B, Appendices55 & 56).

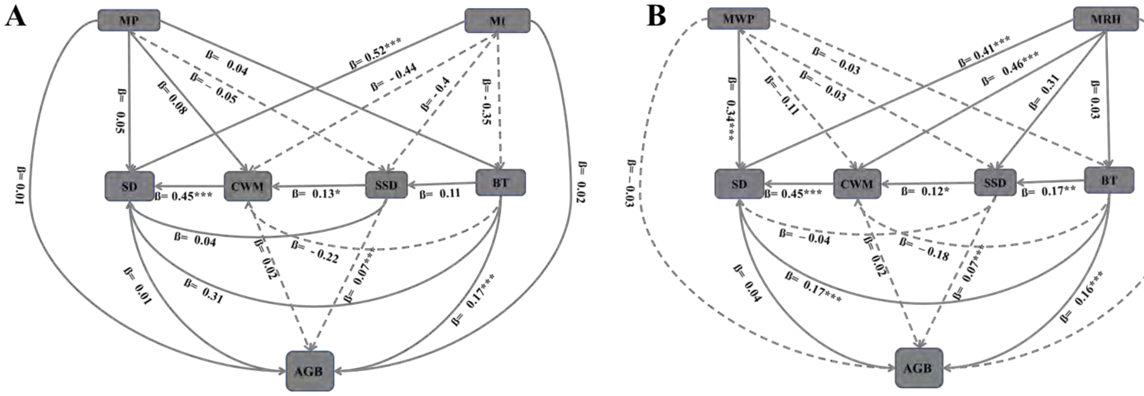


Figure 53 Impact of climate (i.e. mean precipitation (MP), mean temperature (Mt), mean relative humidity (MRH), mean wind pressure (MWP), Shannon diversity (SD), community weighted traits mean (CWM), stand structure diversity (SSD), and big tree (BT) on aboveground biomass (AGB).

(A) Impact of MRH, MWP, SD, CWM, SSD, BT on AGB (B) Impact of MP, Mt, SD, CWM, SSD, BT on AGB. The stars represent the level of significance * > 0.05 **> 0.005 and *** represent >0.0005 respectively.

6.3.3 Effect of soil and multiple biotic drivers of aboveground biomass in the overstorey

Soil dominated with clay loam and rich in organic carbon, nitrogen, and phosphorus leads to an increase in the biotic drivers, i.e., Shannon diversity, community-weighted traits mean, stand structure diversity, and big trees of the overstorey, and enhanced productivity (Figure 54A, Appendices57 & 58). On the other hand soil rich in micronutrients also increases the biotic detriments of the whole community and enhances the aboveground biomass productivity, while macronutrient-rich soil leads to a decline in the biotic determinant of the overstorey and therefore harmful effect on aboveground biomass productivity (Figure 54B, Appendices59 & 60).

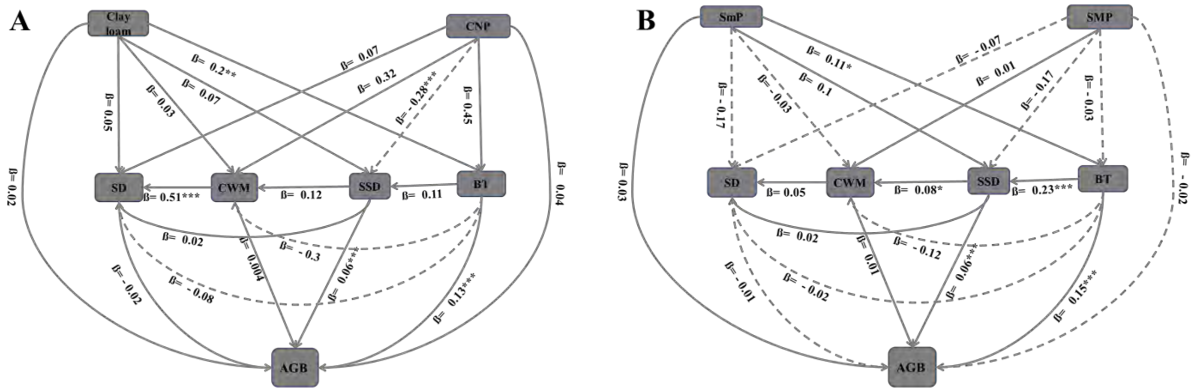


Figure 54 Impact of soil (i.e., soil clay loam, soil carbon nitrogen phosphorous (CNP), soil micro properties (SmP), and soil macro properties (SMP), Shannon diversity (SD), community weighted trait mean (CWM), stand structure diversity (SSD), big tree (BT) on aboveground biomass (AGB) in the overstorey.

(A) Impact of Clay loam, CNP, SD, CWM, SSD, and BT on AGB. (B) Impact of SmP, and SMP, SD, CWM, SSD, and BT on AGB. The stars represent the level of significance * > 0.05 **> 0.005 and *** represent >0.0005 respectively.

6.3.4 Effect of climate on multiple biotic drivers of aboveground biomass in over-storey

An increase in precipitation led to enhanced biotic drivers, i.e., Shannon diversity, community-weighted traits mean, big trees of the overstorey, and enhanced productivity. An increase in temperature also leads to enhanced biotic determinants, i.e., Shannon diversity and big trees of the overstorey, and enhanced productivity (Figure 55A, Appendices61 & 62). On the other side, wind pressure led to a decline in the biotic detriments of the whole community and a decline in the aboveground biomass productivity. An increase in relative humidity leads to a decline in aboveground biomass productivity but they increase the biotic determinant, i.e., community-weighted traits mean of the overstorey and in turn increased aboveground biomass productivity (Figure 55B, Appendices63 & 64).

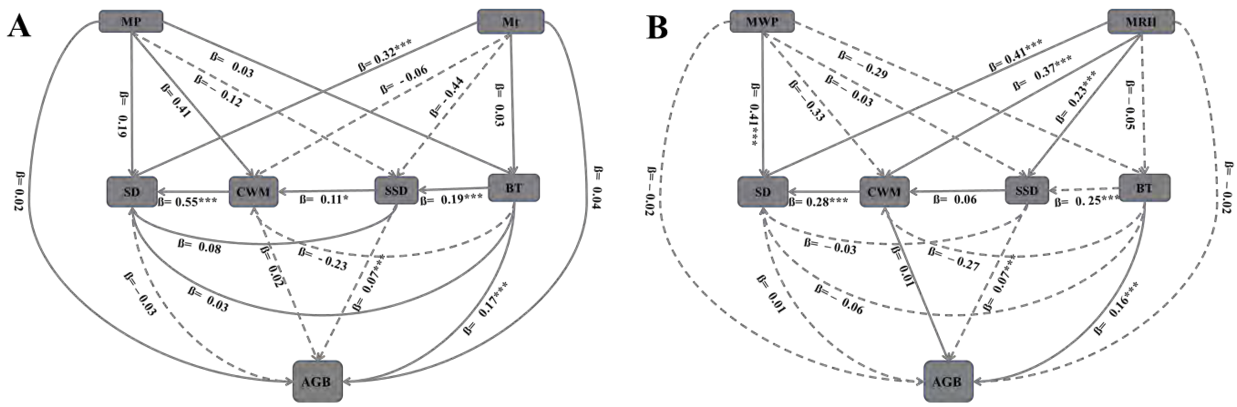


Figure 55 Impact of climate (i.e., mean precipitation (MP), mean temperature (Mt), mean relative humidity (MRH), mean wind pressure (MWP), Shannon diversity (SD), community weighted traits mean (CWM), stand structure diversity (SSD), and big tree (BT) on aboveground biomass in the overstoret strata.

(A) Impact of MRH, MWP, SD, CWM, SSD, BT on AGB. (B) Impact of MP, Mt, SD, CWM, SSD, BT on AGB. The stars represent the level of significance * > 0.05 **> 0.005 and *** represent >0.0005 respectively.

6.3.5 Effect of soil on multiple biotic drivers of aboveground biomass in understorey

Soil dominated with clay loam and rich in organic carbon, nitrogen, and phosphorus has positive effect on the biotic drivers, i.e., Shannon diversity (SD), community-weighted traits mean (CWM), stand structure diversity (SSD), and big tree (BT) of the understorey, and therefore positive association aboveground biomass (AGB) productivity (Figure 56A, Appendices65 & 66). On the other side soil rich in micronutrients (SmP) also has a positive effect on biotic detriments such as SSD, and BT and therefore a positive association with the understorey strata AGB productivity, while soil-rich macronutrient (SMP) has an adverse effect on the biotic determinant of the understorey and therefore harmful effect on aboveground biomass productivity in all forests types (Figure 56B, Appendices 67 & 68).

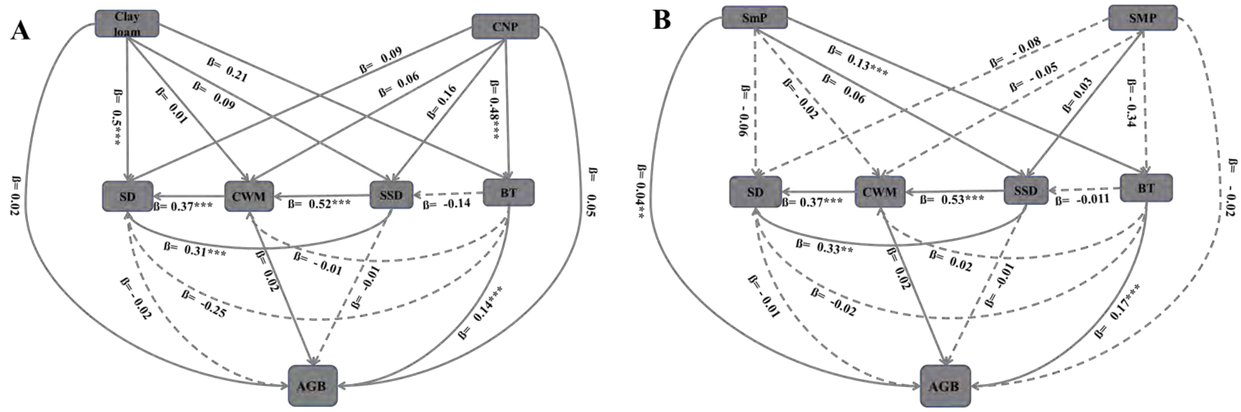


Figure 56 Impact of soil (i.e., soil clay loam, carbon nitrogen phosphorous (CNP), soil micronutrients (SmP), and soil macronutrients (SMP), Shannon diversity (SD), community weighted traits mean (CWM), stand structure diversity (SSD), and big tree (BT), on aboveground biomass in understory.

(A) Impact of Clay loam, CNP, SD, CWM, SSD, and BT on AGB. (B) Impact of SmP, and SMP, SD, CWM, SSD, and BT on AGB in the understorey. The stars represent the level of significance * > 0.05 **> 0.005 and *** represent >0.0005 respectively.

6.3.6 Effect of climate on multiple biotic drivers of aboveground biomass in understorey

An increase in mean precipitation (MP) led to a positive effect on biotic drivers i.e. Shannon diversity (SD), community-weighted traits mean (CWM), big trees (BT) of the understorey, and therefore positive association with aboveground biomass (AGB) productivity. An increase in mean temperature (Mt) also has and positive association with the biotic determinants i.e., SD and CWM of the understorey, and therefore a positive correlation with AGB productivity (Figure 57A, Appendices 69 & 70). On the other side, mean wind pressure (MWP) led to a negative association with the biotic detriments of the understorey and therefore a decline in the AGB productivity. An increase in mean relative humidity (MRH) also led to a decline in AGB productivity but a positive association with biotic determinants i.e. CWM and BT of the understorey and in turn positive effect on aboveground biomass productivity (Figure 57B, Appendices71 & 72).

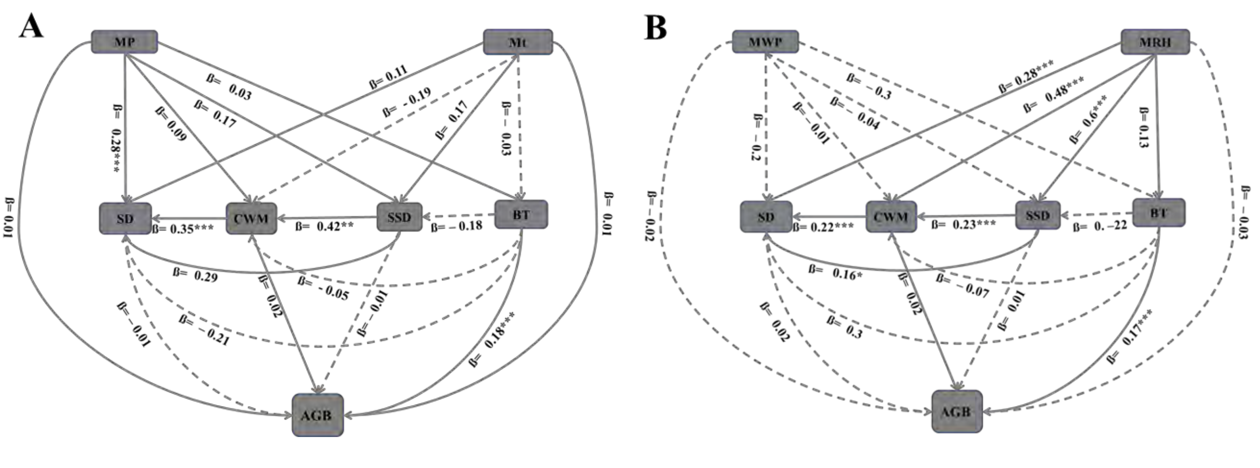


Figure 57 Effect of climate (mean precipitation (MP), mean temperature (Mt), mean wind pressure (MWP), and mean relative humidity (MRH) and Shannon diversity (SD), community weighted traits mean (CWM), stand structure diversity (SSD), and (BT) on aboveground biomass (AGB) in the understorey.

(A) Impact of MP, Mt, SD, CWM, SSD, and BT on AGB in understory. (B) Impact of MWP, MRH, SD, CWM, SSD, and BT on AGB in over storey. The stars represent the level of significance * > 0.05 **> 0.005 and *** represent >0.0005 respectively.

6.3.7 The relationship between biotic determinants and aboveground biomass in the whole community, overstorey, and understory

An increase in biotic determinants, i.e., Shannon diversity (SD), community-weighted traits mean (CWM), stand structure diversity (SSD), and big tree (BT) has a positive correlation with aboveground biomass (AGB) productivity. Similarly, an increase in overstorey biotic determinants, i.e., community-weighted traits mean (CWM), stand structure diversity (SSD), and big tree (BT) has a positive correlation with aboveground biomass productivity while Shannon diversity (SD) has an adverse correlation with aboveground biomass productivity in the overstorey. In the understorey, the biotic determinant, i.e., community-weighted traits mean has a positive correlation with aboveground biomass productivity while Shannon diversity, stand structure diversity, and big trees have adversely correlated with aboveground biomass productivity in the understorey (Figures 58, 59, 60).

6.3.8 The relationship between biotic determinants and aboveground biomass in the whole community

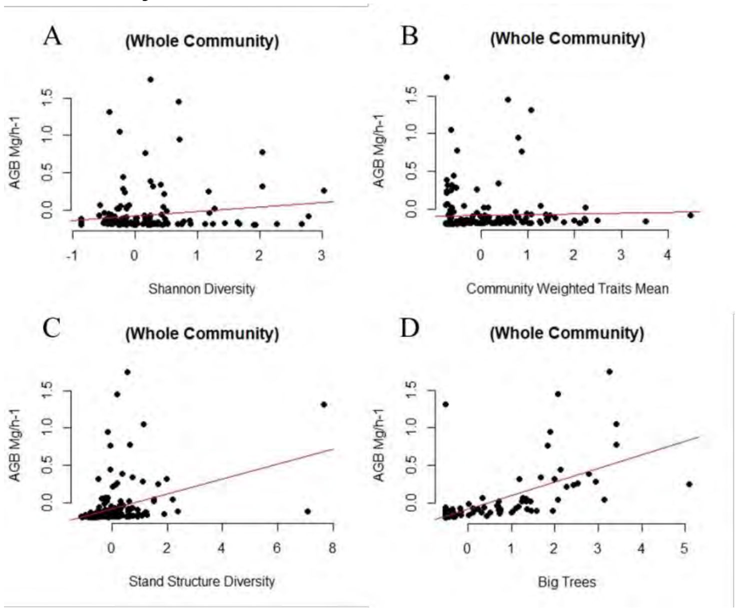


Figure 58 Relationship between biotic variable and aboveground biomass (AGB).

(A) Relationship between Shannon diversity and aboveground biomass (AGB). (B) Relationship between community weighted traits means (CWM) and aboveground biomass (AGB). (C) Relationship between stand structure diversity (SSD) and aboveground biomass (AGB). (D) Relationship between big trees and aboveground biomass

6.3.9 Relationship between biotic determinants and aboveground biomass in the overstorey

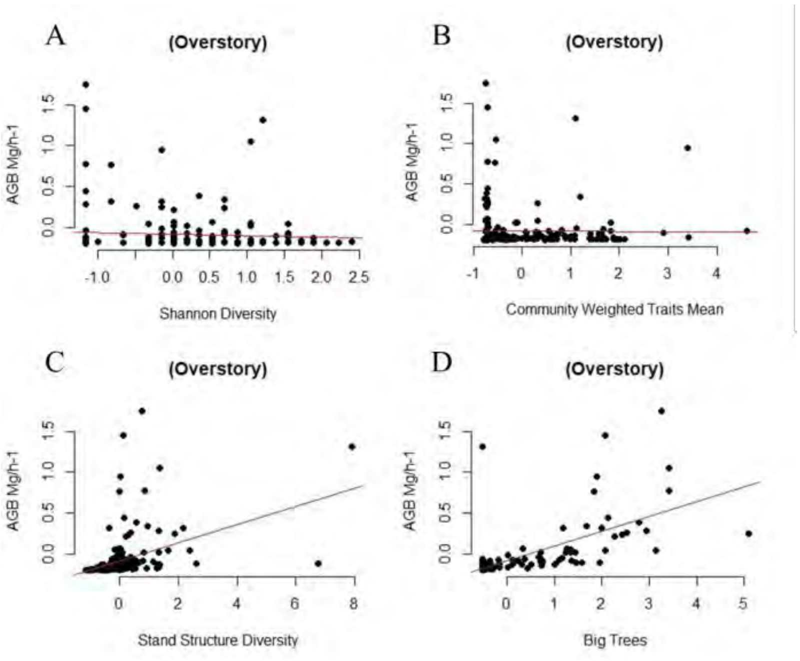


Figure 59 Relationship between biotic variable and aboveground biomass (AGB).

(A) Relationship between Shannon diversity (SD) and AGB. (B) Relationship between communities weighted trait mean (CWM) and AGB. (C) Relationship between SSD and AGB. (D) Relationship between Big Trees and AGB.

6.3.10 Relationship between Biotic determinants and aboveground biomass in the understorey

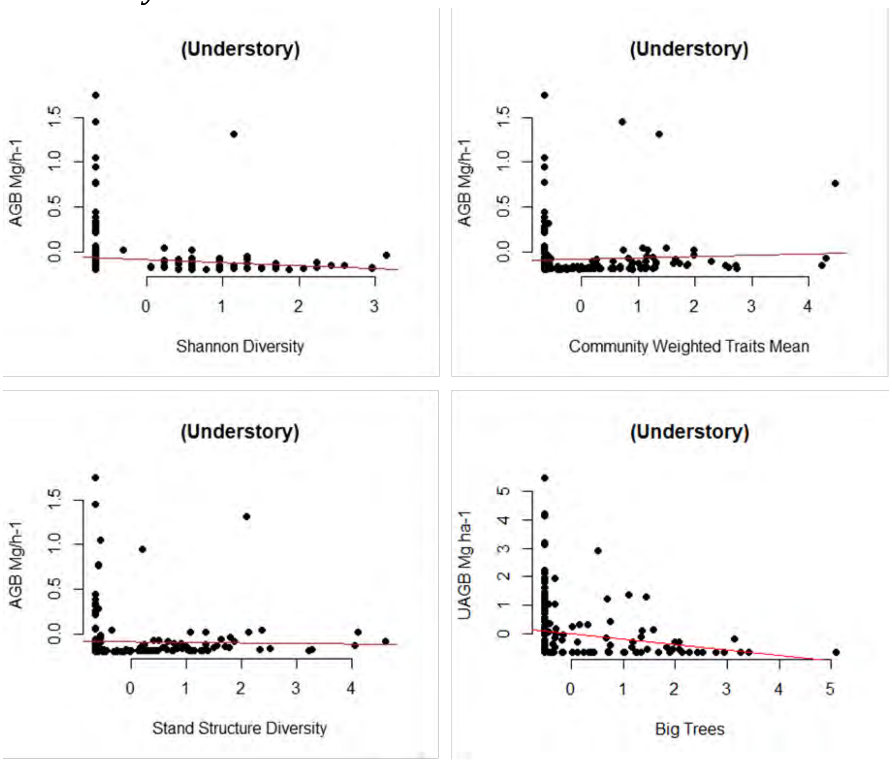


Figure 60 Relationship between biotic variable and aboveground biomass (AGB).

(A) Relationship between Shannon diversity and AGB. (B) Relationship between CWM and AGB. (C) Relationship between SSD and AGB. (D) Relationship between Big Trees and AGB.

6.3.11 Relationship between Soil and aboveground biomass

Soil dominated by clay loam and rich in organic carbon, nitrogen, phosphorus, and other micronutrients leads to enhanced aboveground biomass productivity while macronutrients lead to a decline in aboveground biomass productivity (Figure 61).

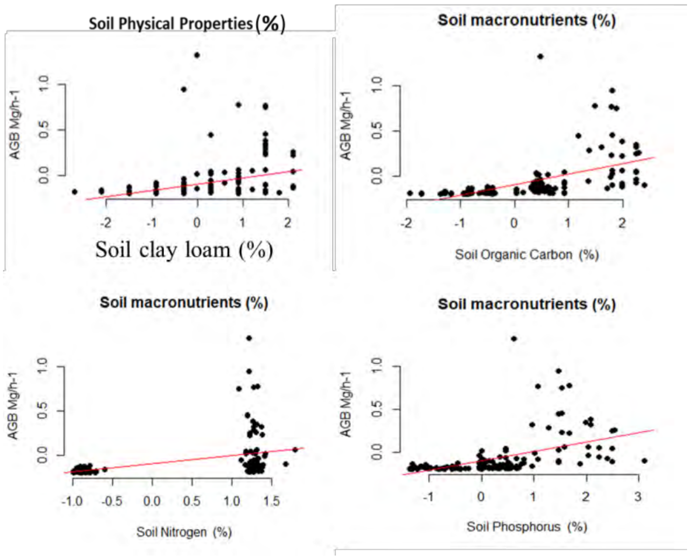


Figure 61 Relationship between soil physicochemical variables and aboveground biomass (AGB)

(A) Relationship between Shannon diversity and AGB. (B) Relationship between CWM and AGB. (C) Relationship between SSD and AGB. (D) Relationship between Big Trees and AGB.

6.3.12 Relationship between climatic variables and aboveground biomass

Climatic variables such as precipitation and relative humidity lead to enhanced aboveground biomass productivity while the increase in temperature and wind pressure leads to a decline in aboveground biomass productivity (Figure 62).

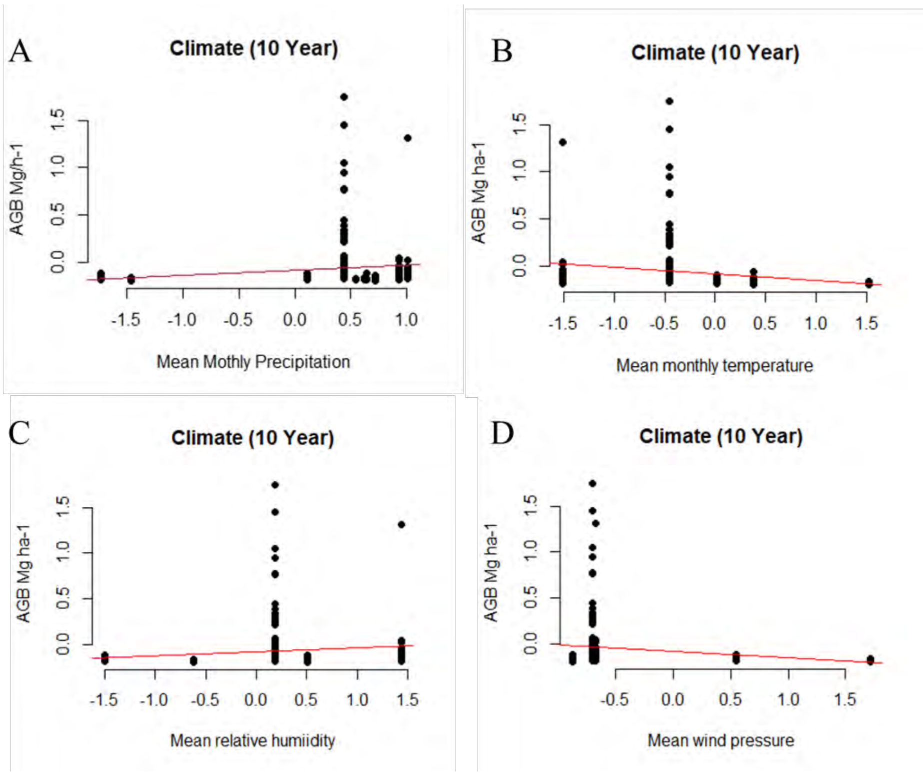


Figure 62 Relationship between climatic variables and aboveground biomass (AGB).

(A) Relationship between Shannon diversity and AGB. (B) Relationship between CWM and AGB. (C) Relationship between SSD and AGB. (D) Relationship between Big Trees and above ground biomass (AGB).

6.3.13 Overall relationship of biotic and abiotic variables of aboveground biomass

Big trees, SSD, and soil are mainly determined by aboveground biomass (Figure 63).

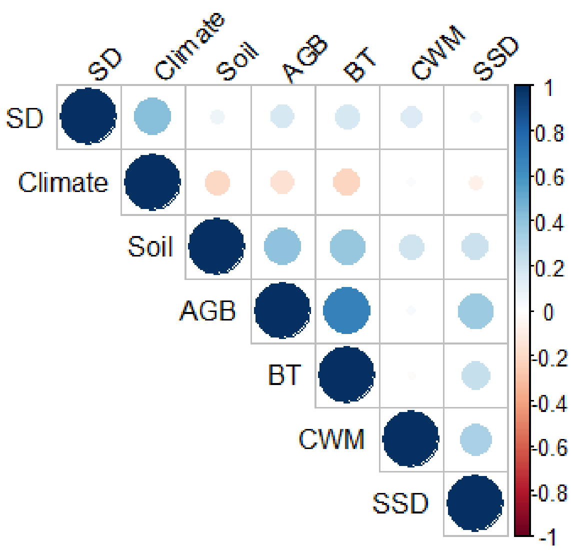


Figure 63 The relationship between biotic and abiotic variables of aboveground biomass.

6.4 Discussion

The main results of our study suggest that aboveground biomass in overstorey, understorey, and whole community strata depends on a variety of biotic factors (such as CWM, SD, SSD, and big trees) and abiotic factors (such as soil and climate) in the natural forest ecosystems of Pakistan.

The effect of multiple biotic and abiotic drivers of aboveground biomass in whole community stratum

In the whole community, we discovered a positive correlation, aligning with our initial hypothesis, between soil physiochemical factors, including clay loam-dominated composition and high levels of carbon, nitrogen, phosphorous, and various micronutrients. This correlation was observed to significantly augment the biotic determinants of aboveground biomass. Specifically, factors such as Shannon diversity, community-weighted traits, mean stand structure diversity, and the prevalence of big trees exhibited a positive association. Consequently, this enhancement in biotic factors played a crucial role in determining the productivity of aboveground biomass. Soil macronutrients (such as cobalt, magnesium, calcium, and sodium) harmed the biotic determinants of aboveground biomass and led to a decline in aboveground biomass productivity. Literature shows that Communities with high aboveground biomass are characterized by species with high adult stature as well as great tree size variation (complex stand structure) in the studied forests (liet al. 2 9) . In combination, the high functional dominance (probably more towards big-diameter trees and less towards small-diameter trees) strongly drove high aboveground biomass at the whole-community level (Ali & Yan 2017a; Fotis et al. 2017). In the current study, we also found a strong positive relationship between Shannon diversity on fertile soil which means that soil played an important role and determined aboveground biomass productivity. Our results are supported by the previous researchers who documented the significant role of larger trees in driving aboveground biomass at the whole community level in regions with high soil nutrient levels (Bartels & Chen 2010; Ali & Yan 2017b; Zhang et al. 2017). In the current study, we also found that soil macronutrients (such as cobalt, magnesium, calcium, and sodium) had a negative effect on aboveground biomass but that they promoted biotic determinants of plants having a conservative strategy of aboveground biomass in dry areas. Plant species are anticipated to adopt a conservative strategy when growing in nutrient-poor soils, while an acquisitive strategy is more likely to be associated with nutrient-rich soils. This differentiation arises from the positive correlation between soil nutrient levels and both plant growth and survival (Poorter & Bongers 2006; Coomes et al. 2009; Reich 2014). In our present investigation, we assessed the impact of mean precipitation on aboveground biomass productivity. We found that mean precipitation had a more substantial effect on enhancing the biotic determinants of aboveground biomass compared to temperature, relative humidity, and wind pressure. Relative humidity and wind pressure have an adverse direct effect on aboveground biomass productivity but relative humidity enhances or positively influences the biotic determinant (such as, community-weighted traits mean, stand structure diversity, and big trees) of aboveground biomass and therefore indirectly via biotic determinants enhances aboveground biomass production. In previous studies, positive associations between species diversity and both mean annual temperature and climatic water availability have been attributed to the integrated hypothesis involving evolutionary rates and biotic interactions, as well as the metabolic theory (Brown et al. 2004; Colwell & Hurtt 1994; Currie et al. 2004; Gillman & Wright 2014; Rohde 1992). However, our findings also lend support to the tolerance-diversity, drought-mortality, and heat-mortality hypotheses because an increase in climatic water availability and mean annual temperature is associated with greater species diversity but a decrease in functional dominance and the inequality in individual tree sizes (Arroyo et al. 1988; Phillips et al. 2010). Additionally, due to spatial factors and gradients that are strongly correlated with mean annual temperature and climatic water availability, our results also strongly endorse the mid-domain effect as an explanation for biotic patterns (Colwell & Hurtt 1994).

The effect of multiple biotic and abiotic drivers of aboveground biomass in the overstorey stratum

In our study, we observed a positive feedback loop between soil physiochemical properties specifically, clay loam-dominated soil with rich carbon, nitrogen, phosphorous, and macronutrient content. However, the enhancement in the biotic determinants of aboveground biomass, including Shannon diversity, community-weighted traits, mean stand structure diversity, and the prevalence of big trees, was notable, excluding micronutrients. This interaction ultimately played a crucial role in determining aboveground biomass productivity. However, big trees have an adverse effect on Shannon's diversity and community-weighted traits mean (CWM). This means that on fertile soil big trees are dominated because they limit the resources for the understory layer of vegetation. The results of the overstorey are almost similar to that of the whole community stratum. The prevailing influence of overstorey trees can diminish the impact of understorey trees on aboveground biomass (Zhang et al. 2017). Species that dominate and possess significant size within the overstorey stratum may efficiently harness light and water resources, consequently reducing the availability of these resources for understorey trees (Bartels & Chen 2010). In this study, we found that soil macronutrients (such as cobalt, magnesium, calcium, and sodium) had an adverse effect on the biotic determinants of aboveground biomass and led to a decline in aboveground biomass productivity. This means that in harsh conditions, such as in the sub-tropical thorn forest and dry temperate pure *P. gerardiana* forest, macronutrients maintain the survival of plant species by enhancing community weighted traits means (i.e., specific leaf area, leaf area, leaf dry matter content, leaf thickness, and wood density) and plant diversity. These findings are similar to those of previously reported studies. Plant species are anticipated to adopt a conservative strategy when growing in nutrient-poor soils, while an acquisitive strategy is more likely to be associated with nutrient-rich soils. This differentiation arises from the positive correlation between soil nutrient levels and both plant growth and survival (Poorter & Bongers, 2006; Coomes et al. 2009; Reich 2014). In this study, we also evaluated the effect of climatic variables and found that precipitation and temperature enhance aboveground biomass productivity while relative humidity and wind pressure caused a decline in aboveground biomass production. These results are similar to what we observed in the whole community stratum because the whole community is in control of the overstorey stratum.

The effect of multiple biotic and abiotic drivers of aboveground biomass in the understorey stratum

In the understorey stratum, we identified a positive correlation between soil physiochemical factors, excluding macronutrients. Specifically, clay loam-dominated soil with high levels of carbon, nitrogen, phosphorous, and micronutrients contributed to an enhancement in the biotic determinants of aboveground biomass. These determinants include Shannon diversity, community-weighted traits, mean stand structure diversity, and the presence of big trees. This, in turn, played a key role in determining the aboveground biomass productivity. However, big trees have an adverse effect on Shannon diversity and community-weighted traits mean and stand structure of the understorey vegetation and therefore reduce aboveground biomass productivity. Our results are consistent with previous studies, particularly in the understorey stratum where slow-growing plant species are prevalent. This is highlighted by a positive correlation observed between the Community-Weighted Mean (CWM) of wood density, representing a conservative growth strategy, and the mean Diameter at Breast Height (DBH), a measure of plant growth. This correlation contributes to an overall increase in aboveground biomass (Ali & Yan 2017). While an increase in taxonomic diversity can lead to higher aboveground biomass, the negative direct impact of Shannon's species diversity on aboveground biomass suggests that in the understorey, the presence of abundant biomass may outcompete weaker competitors, assuming competitive exclusion (Ali et al. 2016). Consequently, the dominance of specific, productive species employing a slow-growing, conservative growth strategy exerts a significant influence on aboveground biomass (Prado-Junior et al. 2016; Ali & Yan 2017). The sluggish growth of understorey plants could be attributed to a significant scarcity of light resources. This shortage is a consequence of the intricate structure of the overstorey, coupled with low functional diversity and substantial aboveground biomass (Bartels & Chen 2010; Ali & Yan 2017a,b; Zhang et al. 2017). In the current study, we found that the understorey aboveground biomass is mostly driven by the soil (such as clay loam-dominated soil, rich in carbon, nitrogen, phosphorous, and other micronutrients) except macronutrients. Macro nutrients had an adverse effect on aboveground biomass productivity in the understorey stratum. Earlier research has indicated that, within the understorey stratum, a species complementarity effect is more pronounced in low-nutrient soils, leading to increased aboveground biomass. This phenomenon is likely a result of the competitive pressures imposed by the overstorey trees (Bartels & Chen, 2010; Ali & Yan 2017b; Zhang et al. 2017). In the current study, we also found that climatic variables (such as mean precipitation and mean temperature) positively influence biotic determinants of aboveground biomass as well as aboveground biomass productivity except for the temperature which produces a decline in big trees and community-weighted traits means. While mean relative humidity and mean wind pressure had adverse effect on aboveground biomass productivity relative humidity enhances the biotic determinant of aboveground biomass and therefore determine aboveground biomass productivity. Earlier research has uncovered that, except for functional divergence, all biotic factors are simultaneously influenced by both climatic water availability and temperature. Consequently, there is a direct positive association between these biotic factors and aboveground biomass (O'Brien 2006). Notably, the negative correlation between climatic water availability and mean annual temperature, representing the interplay of water and energy or drought and heat, emerged as the most influential factor in shaping biotic factors and aboveground biomass within the examined forests, and this agrees with previous studies (Ali et al. 2018; Brookshire & Weaver 2015; Ciais et al. 2005; Gillman & Wright 2014).

6.5 Conclusion

Evaluating the impact of abiotic and biotic variables on aboveground biomass in the whole community, overstorey, and understorey stratum the current study tested different forest types in Pakistan. We demonstrated that abiotic variables (such as soil and climate) drove the multiple biotic determinants and therefore enhanced aboveground biomass productivity. The soil (such as clay loam-dominated soil, rich in carbon, nitrogen, phosphorous, and other micronutrients) except macronutrients and precipitation rather than temperature wind pressure, and relative humidity lead to enhanced aboveground biomass productivity. Soil macronutrients, wind pressure, and relative humidity decline aboveground biomass productivity. Our study indicates that biotic variables play a significant role in enhancing aboveground biomass productivity. However, the presence of large trees is associated with a decrease in understorey stand structure diversity and community-weighted traits-mean. This decline is attributed to resource utilization by dominant plants within the community.

Carbon sequestration and its biotic and abiotic determinant in diffrent forest ecosystems of Pakistan

Introduction

The forest ecosystem plays a crucial role in maintaining clean air by capturing carbon, which benefits all life forms, including humans (Jose 2009). Its influence on global climate is significant, as it regulates the presence of greenhouse gases such as CO_2. When combined with grasslands and peat swamps, forests stand out for storing more carbon than other land-based ecosystems (Lal 2004). Trees within forests absorb CO_2 from the air, storing it as wood, organic soil matter, and other biomass, which aids in reducing global warming and climate change (Zhang et al. 2019). However, disturbances caused by excessive resource extraction in these ecosystems result in the substantial release of CO_2 back into the atmosphere (Daily et al. 2011). Recognizing the importance of carbon sequestration, especially in mitigating global climate change, is crucial (Van de Perre et al. 2018). About 53% of stored carbon is found in temperate and boreal regions, with the remaining 37% located in tropical areas (Sohngen & Sedjo 2006; Li et al. 2021). Half of the Earth's terrestrial carbon sink resides in forest ecosystems (Canadell et al. 2007). Forests not only absorb a substantial amount of CO_2 through photosynthesis but also contribute significantly to fixed carbon in the lithosphere as organic matter (Kulmala et al. 2013). However, only a small portion of the overall stored carbon exists in belowground biomass, litter, and soil (Fan et al. 2008). According to the United Nations Food and Agriculture Organization (FAO), forests hold 234 Pg of carbon above ground, 62 Pg below ground, 41 Pg as deadwood, 23 Pg as litter, and 398 Pg in the forest soils. Forest ecosystems cover the most extensive portion of non-frozen terrestrial land globally. Trees represent the primary component of forest ecosystems and encompass the majority of living biomass in forests. The total biomass of forests is approximately ∼677 Petagrams (Pg), with trees contributing about 8 % of the world‘s total biomass (Kindermann et al. 2008). The scientific community is dedicated to reducing atmospheric CO_2 emissions and finding effective methods to enhance atmospheric quality (Smith et al. 2013). Both biological and geological processes play roles in drawing carbon from the atmosphere. However, the substantial increase in the human population has led to ongoing land degradation and deforestation, resulting in the irreversible loss of crucial forest functions. Plants stand as the primary producers of the planet's biodiversity. They take in atmospheric CO_2, converting it into glucose the fundamental organic molecule for life (Poorter et al., 2016). Degraded forests lead to diminished carbon storage and reduced biodiversity, contributing to global warming and subsequent climate changes (Poorter et al. 2015). Human activities significantly introduce vast amounts of greenhouse gases, particularly CO_2, into the atmosphere (Toochi 2018). The rapid increase in CO_2, methane, and methane dioxide concentrations is a primary driver of global warming (Bernstein et al. 2008). Understanding how various climatic and soil-related factors impact forest diversity, structure, and carbon storage is pivotal in anticipating how forests will respond to global environmental changes. This comprehension is vital for biological conservation and devising forest management strategies aimed at maximizing forest functions and services (Bohn et al. 2018; Coomes et al. 2014b; Keeling & Phillips 2007; Rodrigues et al. 2016). The configuration of forests, their diversity, and the stock of carbon are not solely shaped by natural processes or human disruptions. They are significantly influenced by changes in environmental conditions, such as climate and soil properties (Ali 2019; Corlett 2016; Yuan et al. 2019). For instance, local variations in forest structure, diversity, and carbon content might not always be directly tied to climatic elements like temperature and precipitation but can be more linked to soil composition and topographical features (Clark et al. 1998; Rodrigues et al. 2019). Furthermore, elevation and slope critically influence forest diversity, structure, and biomass by modulating the effects of both climate and soil conditions (Jucker et al. 2018). The complexity of the terrain contributes to environmental screening and habitat variety, ultimately steering the diversity, structure, and carbon reserves within forests (Rodrigues et al. 2016). Local soil properties and micro-climate can vary significantly over a small area, while larger climatic variations span regional or even larger scales. Therefore, the intricacy of the terrain encompasses various gradients of resources (Bohn et al. 2018; Rodrigues et al. 2019; Toledo et al. 2012). At large regional scales, such as across various forest types, the arrangement of forest structure, diversity, and carbon supply is often linked to the breadth of species tolerance, primarily influenced by climatic factors and to a lesser degree by soil conditions (Ali et al. 2018). For instance, temperature decreases as elevation rises, significantly impacting tree growth at higher altitudes (Ali et al. 2019b; Körner 2007). Consequently, climatic moisture becomes a crucial resource for trees, exerting a significant influence on tree species distribution, structure, and functionality (Ali et al. 2018). In essence, forest communities existing in areas with lower temperatures and less climatic moisture may display different variations in individual tree sizes compared to those receiving more precipitation and lower temperatures, or less precipitation and higher temperatures, or vice versa (Phillips et al. 2010). Consequently, diverse climatic factors related to temperature and water might affect species richness, structure, and stock differently, as various species with different individual tree sizes tend to have distinct resource needs in both species-scarce and structurally intricate forests (Bohn et al. 2018; Coomes et al. 2009). When temperature and water-related resources become scarce, tree species tend to engage in more intense competition, prompting variations in forest structural characteristics that improve resource efficiency (Gillman & Wright 2014). Larger trees, alternatively, might hinder the performance of medium and small trees in terms of resource utilization and competitive dominance (Ali et al. 2019a). Beyond temperature and water-related climatic factors, both the chemical and physical properties of the soil play crucial roles in shaping forest diversity, structure, and function. Soil chemistry dictates nutrient availability, influencing plant growth and development (Paoli et al. 2005). On the other hand, soil texture properties determine the availability of water for plant growth and survival (Sanaei et al. 2018). According to the soil nutrients hypothesis, ample soil nutrients can accelerate plant development, leading to increased tree growth and recruitment rates. However, this might also intensify species competition, resulting in higher mortality and turnover rates (Quesada et al. 2012). Nutrient-rich soils can foster greater forest diversity, structural characteristics, and aboveground biomass by supporting varied niche differentiation and facilitation. Yet, these same conditions might decrease these biotic factors due to interspecific competition for available resources in natural forests (Rodrigues et al. 2016). Similarly, the inverse-texture hypothesis suggests that high productivity is found in wet soils with high clay loam content in humid regions, while in arid or dry regions, it is located in dry soils with a high sand or gravel content (Sala et al. 1988).

Research has extensively delved into the influence of climatic and soil-related factors on forest diversity, structure, and carbon reserves across different forest types worldwide (Bohn et al. 2018; Coomes et al. 2014a). Yet, in comparison to various forest types like sub-tropical thorn, sub-tropical broad-leaved, moist, and dry temperate forests, there is notably limited evidence concerning the regional impacts of these factors on diversity, structure, and carbon storage in different forests. The primary drivers of this variation are the changing latitudinal positions and elevations. Pakistan spans a considerable latitudinal range, extending vertically from the 23rd to the 37th parallel lines. Despite its relatively smaller size, it encompasses diverse elevations, from sea level in Karachi to the peak of K2, standing at 8611 meters above sea level. The intermountain valleys and plains are enriched by alluvial soil carried by rivers originating in higher mountain ranges. Within Pakistan, distinct plateaus like Potohar, Balochistan, and the Deosai (the second largest globally after the Tibetan Plateau) possess unique species compositions and varied climatic conditions. Hence, the diverse latitudes and elevations play a defining role in shaping the local climate and soil conditions across different regions within the country. Consequently, Pakistan experiences all four seasons and additionally witnesses summer monsoon rains from July to September (Khan 2020). The mountainous regions cover a substantial 61% of the total geographical land area of the country (Rasul & Hussain 2015). Due to different environmental conditions, Pakistan hosts a variety of forests such as subtropical thorn forest, sub-tropical broad-leaved forest, moist temperate mixed forest, dry temperate conifer forest, dry temperate *Quercus* forest, and dry temperate *Pinus gerardiana* forest. Therefore, a huge research gap and opportunity exist to study these forests, particularly their carbon sequestration along with biotic and abiotic factors. In the current study, we aim to explore how biotic and abiotic variables affect carbon sequestration in the natural forest ecosystems of Pakistan. The object of the current study (1) is to define the role of topography on carbon sequestration. We hypothesized that topography plays an important role in the determination of carbon sequestration. (2) To evaluate the relationship between biotic determinants (such as stand structure diversity, and species richness) and carbon sequestration. We hypothesized that stand structure diversity enhances carbon sequestration while species richness is negatively correlated to carbon sequestration. (3) To evaluate the relationship between soil physicochemical properties and carbon sequestration. We hypothesized that clay loam-dominated and rich soil nutrients have more roles in carbon stock. (4) To define the relationship between climatic variables and carbon sequestration. We hypothesized that precipitation and temperature have more role than relative humidity and wind pressure.

1.4.1 Hypothetical model

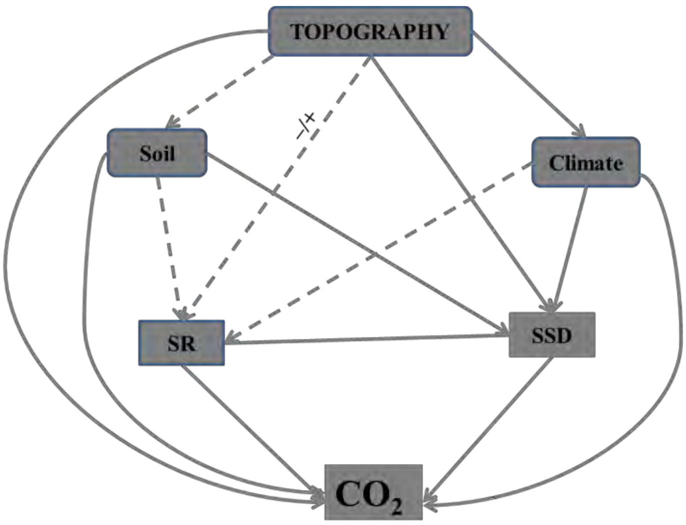


Figure 64 Hypothetical model explaining the effect of soil, climate, species richness (SR), and stand structure diversity (SSD) on carbon sequestration (AGB).

Variables with hypothesized relationships are denoted by -, +, or -/+, accordingly.

1.5 Methodology

Utilizing forest inventory data, we employed plant height and diameter at breast height to calculate the carbon sequestration of each woody tree within each plot (Wright et al. 2004). We then applied equation (1) to weigh the carbon sequestration of these woody plant species over 10 years.

$$W_{ag} = 0.15 \times D2H \qquad (1)$$

The above-ground weight (Wag) is determined based on the diameter of the tree trunk for trees with a diameter greater than 1) and the height of the tree. This weight specifically represents the live tree weight. Initially, we computed the above-ground green weight following the methodology (Clark III et al. 1986).

The belowground system weight of a tree is 20% greater than the above-ground weight. We calculated the total green weight of the tree by multiplying the above-ground weight by 1.2.

$$W_{tgw} = 1.2 \times W_{ag} \qquad (2)$$

The tree‘s total average mass is ~72.5% dry matter, and the moisture content of the tree is 27.5%. Hence, we calculate the tree‘s dry weight by multiplying the total green weight of the tree by .725 (DeWald 2005).

$$W_{Dw} = 0.725 \times W_{tgw} \qquad (3)$$

The average carbon content in the tree is generally 50% of the total tree volume (Toochi et al., 2018; Clark et al., 1986) Thus; we determined the weight of carbon in the tree by multiplying the tree‘s dry weight by 5 % or . 5.

$$W_c = 0.5 \times W_{Dw} \qquad (4)$$

The composition of CO_2 includes one carbon molecule and two oxygen molecules. The atomic weight of carbon is 12.001115, while oxygen has an atomic weight of 15.9994. Therefore, to calculate the weight of CO_2 in trees, we consider the ratio of CO_2 C+2 × O = 43.999915C, which results in 43.999915/12.001115 = 3.6663. Consequently, we established the amount of sequestered carbon dioxide in the tree by multiplying the tree's carbon weight by 3.6663, rounded to 3.67 (Afzal & Akhtar 2013; Toochi 2018).

$$W_{Co2} = 3.67 \times W_C \qquad (5)$$

1.5.1 Statistical analysis

To investigate the impact of topography, climate, soil, species richness (SR), and stand structure diversity (SSD) on carbon sequestration, a structural equation model (SEM) was developed. The goodness of fit (GFI) was assessed using several statistical tests, such as the Chi-squared test, comparative fit index (CFI), standardized root mean square residual (SRMR), Bayesian information criterion (BIC), and Akaike's information criteria (AIC). To determine whether the data were multi-collinear, a variance inflation factor (VIF) test was performed. The VIF test has roughly 2.50 relevance in our case. Linear regression was employed to determine the complete path measurements of the structural equation modeling (SEM) results for each conceptual path (Figure 63). Scatter plots were used by employing the function plot (x, y) to investigate the relationship between biotic and abiotic variables with carbon sequestration. The linear models between y and x were fitted using the function lm (). All the analyses were done in R 3.6.3 (Ali et al. 2023). Before statistical analysis, for normality and linearity, all continuous numerical variables were normalized and standardized and all statistical analysis was done in R 4.0.2 (Antoch 2019).

1.6 Results

1.6.1 The effect of soil on biotic drivers of carbon sequestration

An increase in topography, soil clay loam, soil nitrogen, phosphorous, carbon, and stand structure diversity is highly correlated with higher levels of carbon sequestration while increased species richness is correlated to a decline in carbon sequestration. Moreover, topography also leads to a decline in stand structure diversity of the forest (Figure 64A, Appendices73 & 74). On the other side, topography, soil micro- and macronutrients are also correlated to higher levels of carbon sequestration while species richness is correlated to lower levels of carbon sequestration. However, topography leads to a decline in species richness which leads to a decline in aboveground biomass (Figure 64B, Appendices75 & 76).

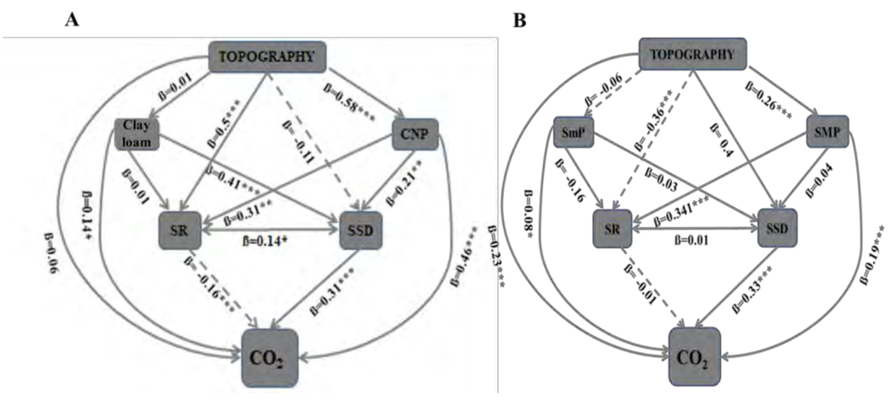


Figure 65 Impact of topography, soil (i.e., clay loam, CNP, SmP, and SMP), SR, and SSD on carbon sequestration.

(A) Impact of topography, soil clay loam, carbon-nitrogen-phosphorous (CNP), species richness (SR), and stand structure diversity (SSD) on carbon sequestration. (B) Impact of topography, soil micro properties (SmP), soil macro properties (SMP), species richness (SR), and stand structure diversity (SSD) on carbon sequestration. The stars represent the level of significance * > 0.05 **> 0.005 and *** represent >0.0005 respectively.

1.6.2 The effect of soil on biotic drivers of carbon sequestration

An increase in precipitation and temperature significantly correlated with carbon sequestration but the role of mean monthly precipitation (MP) is more important than the mean monthly temperature (Mt) (Figure 65A, Appendices77 & 78). Similarly, an increase in mean monthly wind pressure (MWP) and mean monthly relative humidity (MRH) leads to an enhancement in carbon sequestration but relative humidity indirectly enhances carbon sequestration via abiotic determinants (Figure 65B, Appendices79 & 80).

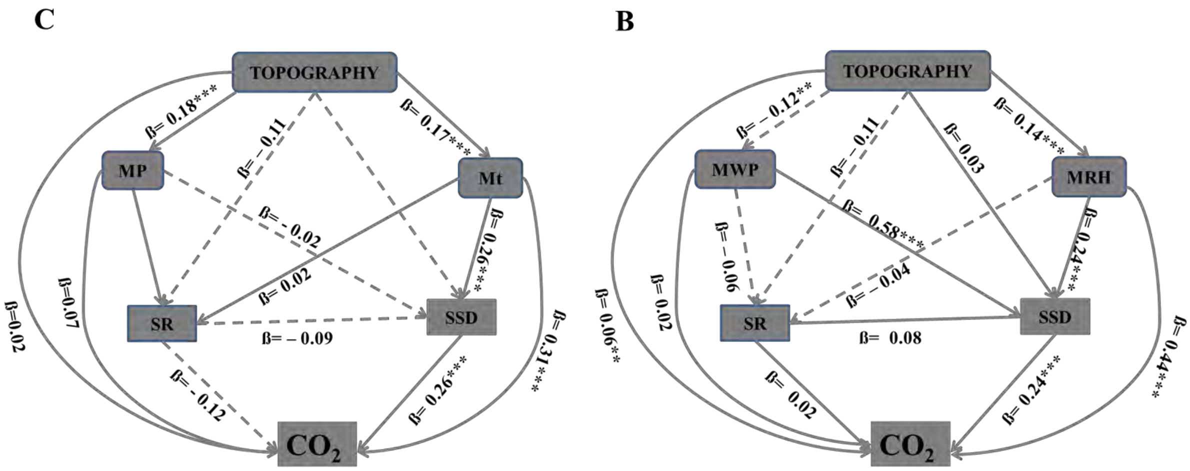


Figure 66 Impact of topography, climate (i.e., MP, Mt, MWP, and MRH), SR, and SSD on carbon sequestration.

(A) Impact of topography, Mean monthly precipitation (MP), mean monthly temperature (Mt), species richness (SR), and stand structure diversity (SSD) on carbon sequestration (B) Impact of topography, mean monthly wind pressure (MWP), mean monthly relative humidity (MRH), species richness (SR), and structure diversity (SSD) on carbon sequestration. The stars represent the level of significance * > 0.05 **> 0.005 and *** represent >0.0005 respectively.

1.6.3 The relationship between biotic determinants and carbon sequestration

An increase in stand structure diversity (such as diameter at breast height, plant height, and crown area) enhances carbon sequestration. While species richness is not significantly correlated with carbon sequestration in all the forest types (Figure 66).

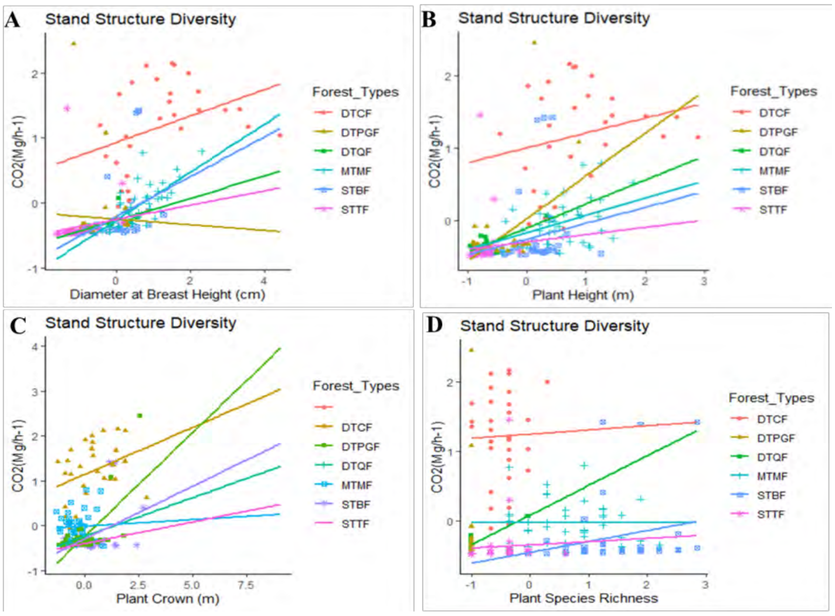


Figure 67 Relationship between biotic variables and carbon sequestration.

(A) Relationship between diameter at breast height and carbon sequestration. (B) Relationship plant height and carbon sequestration. (C) Relationship between plant crown and carbon sequestration. (D) Relationship plants species richness and carbon sequestration. STBF = Sub-tropical broad-leaved forest, STTF= Sub-tropical thorn forest, DTCF= Dry temperate conifer forest, MTMF= Moist temperate mixed forest, DTQF= Dry temperate *Quercus* forest, DTPGF= Dry temperate *Pinus gerardiana* forest.

1.6.4 The relationship between topography and carbon sequestration

The increase in latitude leads to an increase in carbon sequestration except in the sub-tropical broad-leaved forest (STBF). Similarly, longitude also leads to an increase in carbon sequestration in dry temperate conifer forests (DTCF), moist temperate mixed forests (MTMF), and dry temperate *Quercus* forests (DTQF). While subtropical broad-leaved forest (STBF), sub-tropical thorn forest (STTF), and dry temperate *Pinus gerardiana* forest (DTPGF) longitudes lead to a decline in carbon sequestration. An increase in elevation and slope angle leads to enhanced carbon sequestration only in dry temperate conifer forests. While increase in elevation and slope angle leads to a decline in carbon sequestration in all other forest types (Figure 67).

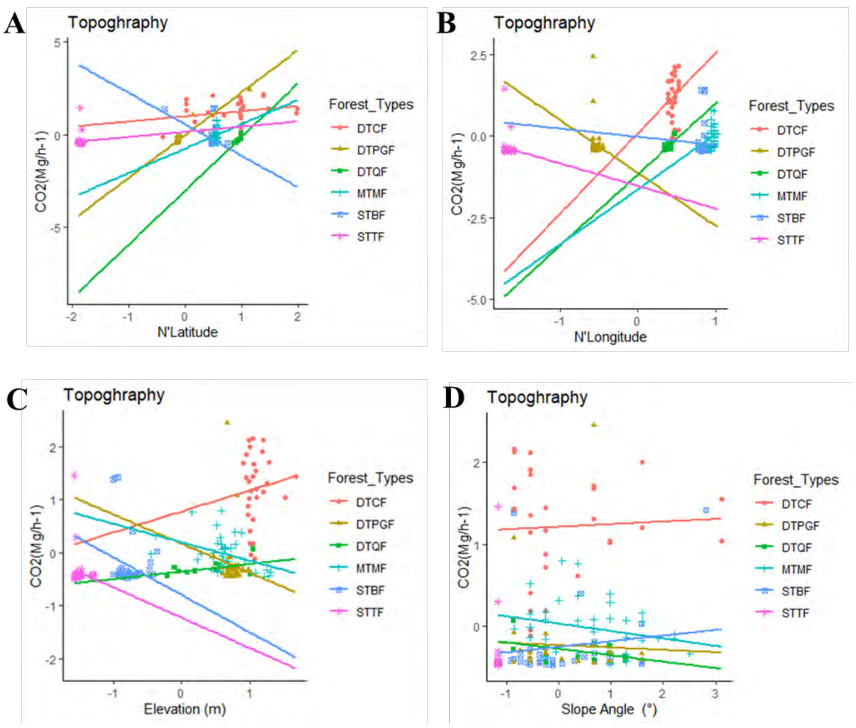
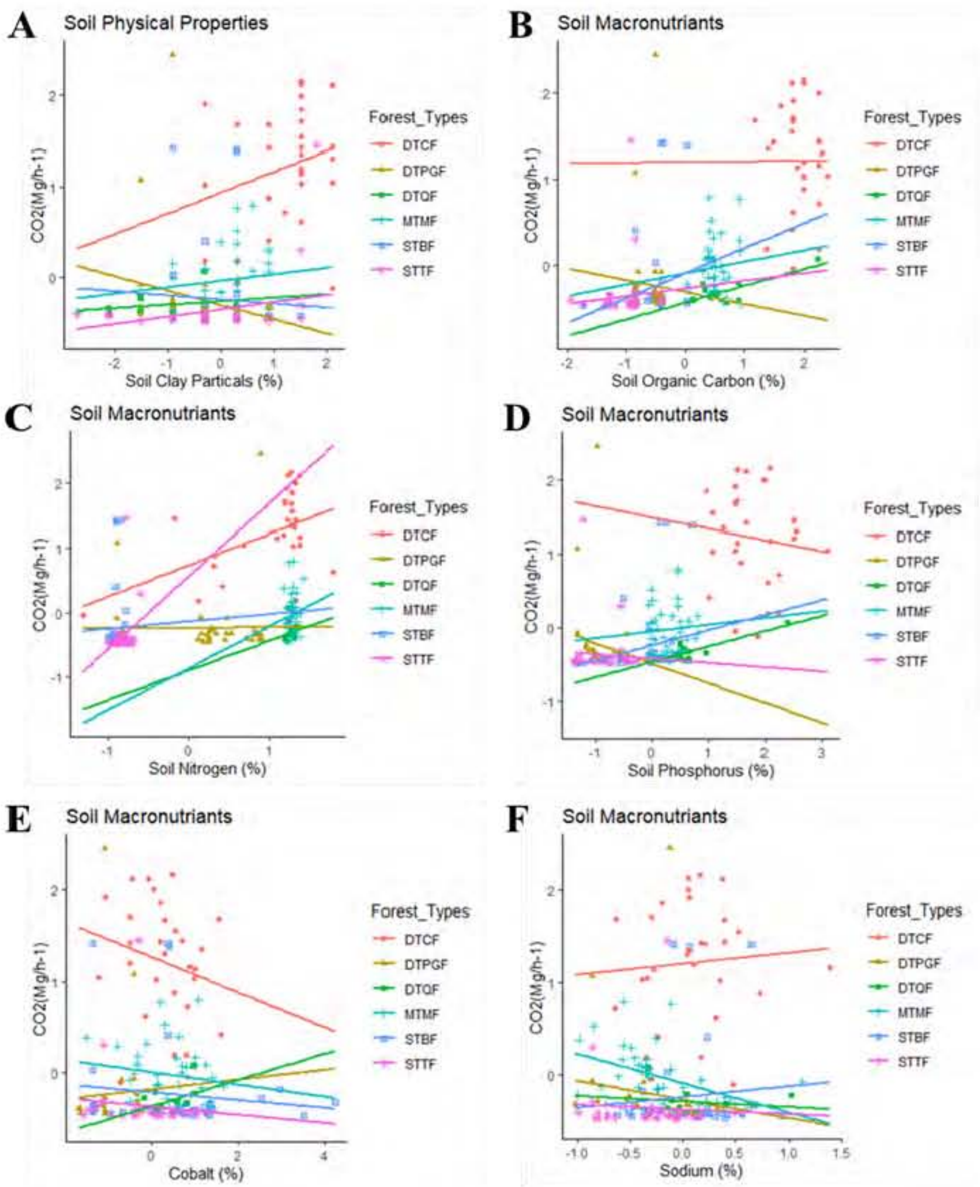


Figure 68 Relationship between topographic variable and carbon sequestration.

(A) Relationship between latitude and carbon sequestration. (B) Relationship longitude and carbon sequestration. (C) Relationship between elevation and carbon sequestration. (D) Relationship between slope angle and carbon sequestration. STBF = Sub-tropical broad-leaved forest, STTF= Sub-tropical thorn forest, DTCF= Dry temperate conifer forest, MTMF= Moist temperate mixed forest, DTQF= Dry temperate *Quercus* forest, DTPGF= Dry temperate *Pinus gerardiana* forest.

1.6.5 The relationship between soil physicochemical properties and carbon sequestration

An increase in soil clay loam and macronutrients (such as soil carbon, nitrogen, and phosphorus) leads to enhanced carbon sequestration in all the forest types. The increase in other macronutrients such as cobalt, sodium, magnesium, and calcium leads to a decline in carbon sequestration except in dry temperate conifer forests. Whereas, sodium and magnesium lead to enhanced carbon sequestration. Micronutrients such as copper lead to enhance carbon sequestration while nickel, manganese, and chromium lead to a decline in carbon sequestration in all the forest types (Figure 68).



A
Soil Physical Properties
Soil Clay Particals (%)
B
Soil Macronutriants
Soil Organic Carbon (%)
C
Soil Macronutriants
Soil Nitrogen (%)
D
Soil Macronutriants
Soil Phosphorus (%)
E
Soil Macronutriants
Cobalt (%)
F
Soil Macronutriants
Sodium (%)
CO2(Mg/h-1)
Forest_Types
DTCF
DTPGF
DTQF
MTMF
STBF
STTF

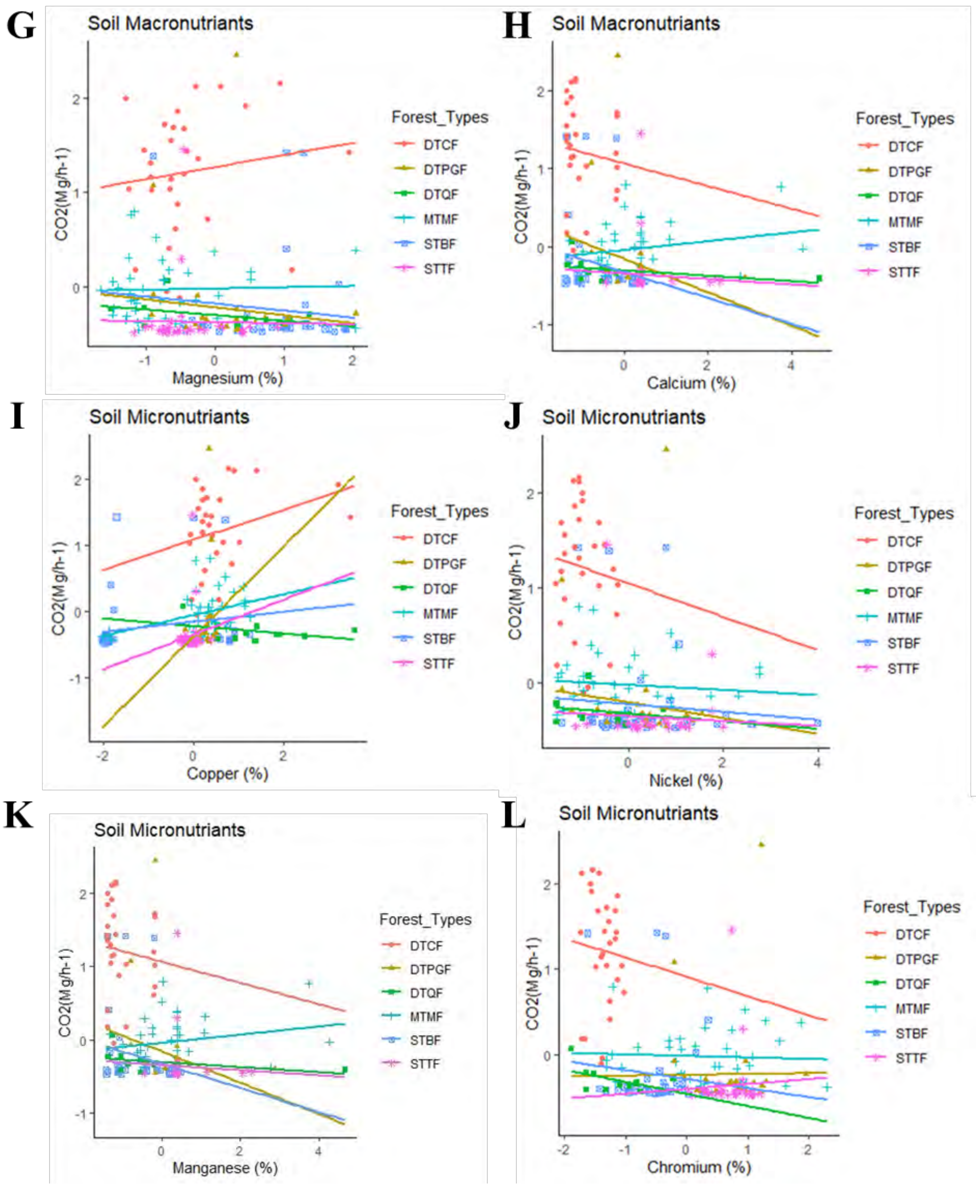


Figure 69 Relationship between topographic variable and carbon sequestration.

(A) Relationship between soil clay loam and carbon sequestration. (B) Relationship between soil carbon and carbon sequestration. (C) Relationship between nitrogen and carbon sequestration. (D) Relationship between phosphorous and carbon sequestration. (E) Relationship between cobalt and carbon sequestration. (F) Relationship between sodium and carbon sequestration. (G) Relationship between magnesium and carbon sequestration. (H) Relationship between calcium and carbon sequestration. (I) Relationship between copper and carbon sequestration (J) Relationship between nickel and carbon sequestration. (K) Relationship between manganese and carbon sequestration. (L) Relationship between chromium and carbon sequestration. STBF = Sub-tropical broad-leaved forest, STTF= Sub-tropical thorn forest, DTCF= Dry temperate conifer forest, MTMF= Moist temperate mixed forest, DTQF= Dry temperate *Quercus* forest, DTPGF= Dry temperate *Pinus gerardiana* forest.

1.6.6 *The relationship between climates and aboveground biomass*

An increase in temperature, precipitation, wind pressure, and relative humidity leads to an increase in carbon sequestration except in dry temperate *Pinus gerardiana* forest whereas carbon sequestration leads to a decline in increase in temperature and precipitation (Figure 69)

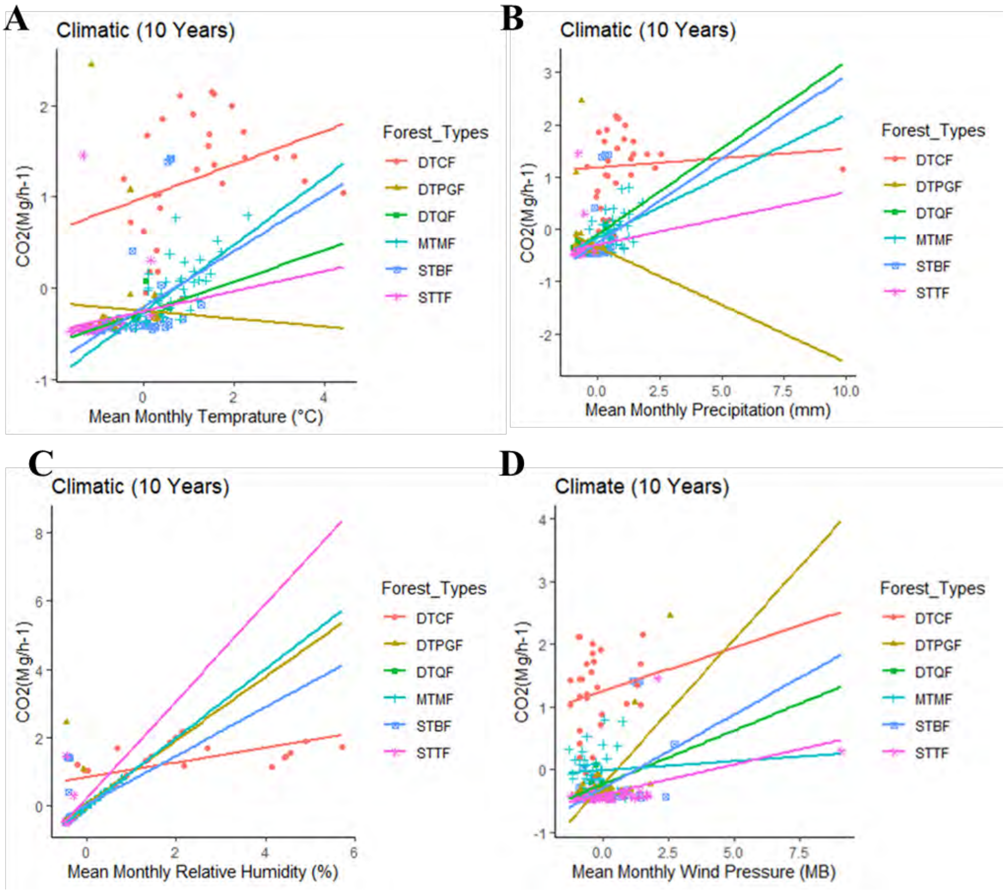


Figure 70 Relationship between climatic variable and carbon sequestration.

(A) Relationship between mean monthly temperature and carbon sequestration. (B) Relationship between mean monthly precipitation and carbon sequestration. (C) Relationship between mean monthly relative humidity and carbon sequestrations. (D) Relationship between mean wind pressure and carbon sequestration. STBF = Sub-tropical broad-leaved forest, STTF= Sub-tropical thorn forest, DTCF= Dry temperate conifer forest, MTMF= Moist temperate mixed forest, DTQF= Dry temperate *Quercus* forest, DTPGF= Dry temperate *Pinus gerardiana* forest.

1.6.7 *Overall relationship of biotic and abiotic variables of aboveground biomass (AGB).*

Soil topography and SSD are mainly determined by aboveground biomass (Figure 71).

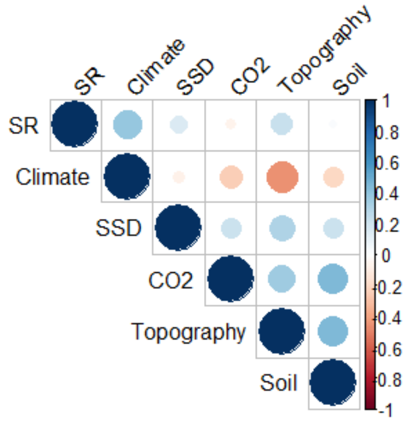


Figure 71 The relationship between biotic and abiotic variables of carbon sequestration.

1.7 Discussion

This is the complete estimation of carbon sequestration in different forest types along a climate and soil gradients across Pakistan, i.e., sub-tropical thorn forest, sub-tropical broad-leaved forest, moist temperate mix forest, dry temperate conifer forest, dry temperate *Quercus* forest, and dry temperate *Pinus gerardiana* (Chilgoza) forest along regional-scale topographic gradients in Pakistan. We evaluate the impact of biotic (such as species richness, and stand structure diversity) and abiotic (such as topography, climate, and soil). It indicates that biotic as well as abiotic variables are strongly and significantly correlated with carbon sequestration in all the forest types.

Effect of topography on carbon sequestration in different forest types

As hypothesized, topography enhances more or less carbon sequestration in most of the forest types except elevation which has an adverse effect on carbon sequestration. Carbon sequestration only increases with an increase in elevation in the dry temperate conifer forest. In addition, an increase in topography leads to a decline in stand structure diversity and species richness more or less. This means that moving away from the equator to the north the biomass increases. The adverse effect of elevation means that an increase in elevation leads to alpine regions where no trees or vegetation are found because of the cool temperature and short growing season. As elevation increases a decrease is noted in carbon sequestration. Only in dry temperate conifer forest elevation leads to enhanced carbon sequestration because the forest is found in the great Hindu Kasha mountains and up to a limit vegetation quality increases. Like previous regional studies, observations on Mt. Changbai indicate a significant and inverse relationship between carbon sequestration and both above-ground and below-ground living biomass concerning elevation. This connection is likely due to the temperature decline along the elevation gradient, limited water availability, and the cooler conditions that restrict tree growth at higher elevations (Luo et al. 2005). An important factor could be the reduced presence of carbon dioxide at higher elevations, leading to lower carbon absorption by trees in those areas. Several researchers have noted a decrease in carbon sequestration as elevation increases (Moser et al. 2007). Factors such as water scarcity, exposure, cooler temperatures, reduced transpiration rates, poor soil quality, and lower soil temperatures can limit growth (Way & Oren 2010). However, these findings contrast with studies in other tropical forests, where biomass reduces with elevation, consequently leading to a decline in carbon sequestration (Girardin et al. 2010).

Effect of biotic variables on carbon sequestration in different forest types

The effect of biotic variables such as stand structure diversity is significantly correlated with carbon sequestration while species richness is not positively correlated and leads to a decline in carbon sequestration. As hypothesized, higher tree diameters at the breast height and tree height are correlated with higher carbon sequestration. Our previous study in different forest types also indicates that tree diameter at breast height and tree height significantly correlated with carbon sequestration in different forest types (Ali et al. 3023). In a study within sub-tropical forests, it was discovered that tree height and diameter at breast height play a significant role in regulating carbon sequestration in forest ecosystems (Xu et al. 2018). Contrarily, in our study, we observed a notable negative correlation between carbon sequestration and species richness. This aligns with findings from the Garwal region, which also reported a negative relationship between species richness and carbon sequestration (Sharma et al. 2016). Potter and Woodall, conclusion emphasizes the importance of species richness but suggests it might not be the most pivotal metric for understanding biodiversity and carbon sequestration (Potter & Woodall 2014). Our results echo this similarity, indicating a negative relationship between carbon sequestration and species richness. However, in our study, carbon sequestration was significantly influenced by tree height and DBH. This aligns with another study that strongly supports our findings, indicating a direct correlation between carbon density and tree DBH and height (Måren & Sharma 2021). Similarly, another previous study concluded that carbon sequestration in the forest is mainly driven by tree height, DBH, crown area, and stand density in the reserve forest of Pakistan (Ali et al. 2022). Nevertheless, other studies reported no correlation between carbon sequestration with species richness and tree height, suggesting that carbon sequestration has no relationship with SR in forest communities.

Effect of soil physicochemical properties on carbon sequestration in different forest types

We found that the effect of soil on carbon sequestration in different forest types is positive. This means that an increase in soil fertility leads to an increase in carbon sequestration. However, as hypothesized in soil clay loam and macronutrients have a more strong effect on carbon sequestration than micronutrients. In the subtropical thorn forest carbon sequestration is mainly driven by soil clay loam, macronutrients such as carbon, and nitrogen, and micronutrients such as copper, and chromium. Whereas in sub-tropical broad-leaved forests, carbon sequestration is mainly driven by the soil clay loam, macronutrients such as carbon, nitrogen, phosphorus, sodium, and micronutrients such as copper. In dry temperate conifer forests, carbon sequestration is mainly driven by the soil clay loam, macronutrients such as carbon, nitrogen, magnesium, sodium, and micronutrients such as copper. In dry temperate Quercus forests, carbon sequestration is mainly driven by the soil clay loam, and macronutrients such as carbon, nitrogen, and cobalt. In moist temperate mixed forests, carbon sequestration is mainly driven by the soil clay loam, macronutrients such as carbon, nitrogen, magnesium, and micronutrients such as copper and manganese. In pure *Pinus gerardiana* forest carbon sequestration is mainly determined by macronutrients such as cobalt and micronutrients such as copper. Micronutrients such as copper lead to enhance carbon sequestration while nickel, manganese, and chromium lead to a decline in carbon sequestration in all the forest types. Other studies support the significance of soil textural properties and fertility in determining carbon stock in species-poor forests. It's widely understood that sandy soils in arid regions often lead to low vegetation diversity, structure, and productivity due to irregular precipitation patterns and poor nutrient availability caused by soil textural properties (Li et al. 2013; Sanaei et al. 2018). Soil textural properties in moist temperate, semi-humid, and semi-arid regions present various physical and chemical constraints such as poor soil stability, limited nutrient holding capacity, and lower aboveground biomass. This reinforces the idea that in large-scale species-rich forests, climate rather than soil primarily influences forest diversity, structure, and biomass (Ali et al. 2018; Poorter et al. 2017), and this understanding can extend to species-poor forests.

Effect of climate on carbon sequestration in different forest types

As hypothesized we found that climate has a major role in the determination of carbon sequestration in different natural forest types. Our results indicate that carbon sequestration increases with an increase in precipitation, temperature, relative humidity, and wind pressure except in dry temperate pure *Pinus gerardiana* forest. Where an increase in temperature and precipitation leads to a decline in carbon sequestration. in dry temperate pure *Pinus gerardiana* forest carbon sequestration is mainly driven by wind pressure and relative humidity because these forests are located on cool dry sites of the country and these areas are mostly cooled and dry most of the year. These results are supported by the general narration that in abiotic factors climate mainly determines carbon stock in the forest ecosystem (Poorter et al., 2017), but the role of soil-related factors. In the current study, we found that in harsh climatic conditions, carbon sequestration is mainly dependent on soil-related factors such lay dominated soil, rich copper, chromium, carbon, and nitrogen and less dependent on climatic factors such as relative humidity. Previous studies show that aboveground carbon stock increases with an increase in temperature-related climatic factors and decreases with water-related factors (Ali, et al. 2020). These results are in contrast with our studies. These differences may be due to the current study conducted in different forest types of Pakistan where the climatic condition and relationship with carbon sequestration is different as compared to studies from other parts of the world. We only found that precipitation and temperature both lead to decrease carbon sequestration in pure *Pinus gerardiana* forest where carbon sequestration is regulated by relative humidity and wind pressure. Our results are supported by previous studies that temperature usually decreases along an increasing elevation gradient, which controls tree growth at higher elevations (Ali et al. 2019b; Körner 2007). Climatic water stands as a critical resource for trees, profoundly impacting the distribution, structure, and function of tree species (Ali et al. 2018). Consequently, forest communities existing in areas with lower temperatures and less climatic water might exhibit varying individual tree size patterns compared to those experiencing more precipitation and temperature, or less precipitation and higher temperatures, and vice versa (Phillips et al. 2010). Thus, different temperature and water-related climatic factors might affect species richness, structure, and stock in distinct ways due to varying resource-use requirements among species in both species-poor and structurally complex forests (Bohn et al. 2018; Coomes et al. 2009). When temperature-related and water-related resources become limited, tree species tend to compete more intensely, resulting in enhanced efficiency in resource utilization and a consequent variation in forest structural attributes (Gillman & Wright 2014).

1.8 Conclusion

This study indicates that topographers expect elevation and stand structure diversity rather than species richness to enhance carbon sequestration. Climatic-related factors like temperature precipitation, relative humidity, and wind pressure have more role than soil-related factors. More importantly, this study evaluates that in harsh climatic conditions relative humidity and soil such as clay loam-dominated soil, soil chromium, copper, carbon, and nitrogen-driven carbon sequestration in dry temperate and sub-tropical thorn forest types. It has been concluded that in forest ecosystems carbon sequestration is mainly dependent on climatic-related factors but the role of soil cannot be ignored, in harsh climatic conditions soil is primarily driven by carbon sequestration

Chapter 8

Synthesis

Forests play a crucial role in maintaining the planet's well-being, contributing significantly to 75% of terrestrial gross primary productivity (GPP) and housing 80% of Earth's total plant biomass. Notably, these ecosystems store more carbon in their biomass and soils than is present in the Earth's atmosphere itself (Pan et al. 2011a; FAO 2010; Beer et al. 2010). Beyond their ecological significance, forests provide essential ecosystem services to humanity. These services include the provision of food and raw materials such as wood and medicine, along with intangibles like clean water, spiritual and aesthetic inspiration, and climate stabilization (Jackson et al. 2005; McKinley et al. 2011). It is noteworthy that over 200 million people living in impoverished conditions directly rely on forests for their energy, shelter, and livelihood. Forests have a global presence, spanning various regions. Asia, including Asian Russia, boasts the largest share, covering 31% of Earth's forested area, followed by South America at 21%, Africa at 17%, North and Central America at 17%, Europe at 9%, and Oceania at 5% (SCBD 2010; FAO 2010). In recent decades the relationships between forest diversity, structure, and function have been one of the major topics in the field of ecosystem functioning research. Nevertheless, a lot of disputes and controversies have still existed in it (Hooper, Chapin Iii et al. 2005). Forest contains an extremely huge ecosystem from the root to the canopy top and provides a large biotic surface. Trees are the explanatory example of forest ecosystem function and they modify their environment because of their absolute size (Nadrowski, Wirth, et al. 2010). In addition, forests link the troposphere with the deep groundwater and regulate climate, improving soil development, initiating nutrients and carbon cycles, and producing organic matter. The relationship between forest diversity, structure, and function might vary in different ecosystems (Steinbeiss, et al. 2008). The Variation is not only because of the natural processes and anthropogenic disturbance but is great because of changes in environmental conditions i.e. climate and soil. To understand the effect of various climatic and soil conditions on forest diversity, structure, and function it is important to predict how forests will respond to global environmental change and influence forest function and services. At a small or local scale forest diversity, structure, and function might not be determined by climatic conditions e.g. temperature and precipitation but might be determined by topographic and soil conditions. It is due to topographic factors, such as slope and elevation, and has been identified as a major spatial determinant influencing changes in forest diversity structure and function as a result of soil and climatic changes. At large regional scale forest diversity, structure, and function might be greatly associated with climatic conditions and less extent to soil conditions. It is because of climatic water which is a main factor for trees and could intensively influence tree species distribution structure, and function. Along with water and temperature-related climatic factors, soil properties are also important inducing factors of forest diversity structure and function because chemical factors of soil define nutrient availability (Ali, et al. 2020). However, if forests are confronted with escalated species extension, will future forests be able to sustain their functions and services? In a world with fewer tree species, are we at risk of approaching lower levels of forest functions and services? This is the central question of forest diversity structure and function research. This new field arose at the start of the 1990s (Solan, Godbold et al. 2009).

Literature showed that there is no such detailed work on these topics from Forests of Pakistan although nature blessed Pakistan with a diverse type of geography and weather with an elevation range from 0 to 8611-meter height. Therefore, we found a huge research gap and opportunity to test the relationship between forest diversity structure and function in a diverse type of climate and soil condition across the country for the first time. In the current research, we are focusing on the relationships between forest diversity, structure, and function in different types, such as Dry Sub-tropical Forests, Moist Sub-tropical broad-leaved Forests, and moist-temperate mix Forests, Dry Temperate coniferous Forests, and Dry Temperate pure *Pinus garadiana* Forest. In the current project, we synthesize the results in the following sections.

Relationship between Environment, Diversity, and Aboveground Biomass (AGB)

The current study, which synthesizes a variety of environmental parameters, investigates the complex effects of species diversity, stand structure diversity, and topography on aboveground biomass in forest ecosystems. Reiterating Whittaker's observation that topography influences forest biomass and composition, the beneficial effects of elevation, slope angle, latitude, and longitude are noted (Whittaker, 1956). Protected from human and environmental disturbances, forests in hilly locations and inner valleys have higher aboveground biomass, underscoring the crucial role that topography plays in determining spatial patterns of temperature, precipitation, and soil fertility (Ali et al., 2020; Ali et al., 2023; Jucker et al., 2018). The study delves deeper into the topographic parameters of slope angle, elevation, longitude, and latitude and their critical roles in determining the structure and function of forest diversity. Topography-folded forests provide significant timber and related services in addition to increasing aboveground biomass and lowering atmospheric carbon levels (Bohn et al., 2018). The brief overview highlights the complex relationships that exist between topography and the ecological services that forests offer. The study examines how soil and climate affect aboveground biomass and finds that longer growing seasons, higher mean annual precipitation, rising temperatures, and improved forest stand structure are all positively correlated with aboveground biomass (Bohn et al., 2018; Luo, 2007; Poorter et al., 2017; Ali et al., 2019b). This highlights the wide relevance of these findings by reinforcing the global significance of climate variables in generating forest spatial patterns and the sensitivity of certain tree species to temperature extremes (Holdridge, 1967; Whittaker, 1975; Sakai, 1982; Woodward, 1987; Calder, 1998). The analysis emphasizes how crucial forests are to maintaining a variety of environmental benefits, such as aesthetics, hydrological balance, water and air quality, climate regulation, scenic beauty, and CO_2 absorption, all of which enhance human well-being. Although large-scale research highlights how climate significantly affects productivity and biomass stocks, the synthesis recognizes how significantly soil conditions vary at smaller scales (Toledo et al., 2011; Burrough, 1983). The study is consistent with previous research in that it looks at the beneficial effects of soil fertility on biomass productivity, particularly in poor soils such as those found in the Guiana Shield. It also highlights the role that lights, water availability, and soil nutrients play in determining species distribution and biodiversity (Quesada et al., 2011; van Kekem et al., 1996; Ali et al., 2019; Ali et al., 2020; Poorter et al., 2015; Stegen et al., 2011). The summation emphasizes how abiotic variables shape relationships between species diversity, regional aboveground biomass, and tree size changes dynamically. Assessing how the overstorey affects understory vegetation, the study finds that it negatively affects light availability and resource availability, which in turn affects the understory's aboveground biomass. The summary acknowledges the vertical complexity of forest structure and how it affects the distribution of biomass at different strata (Ali et al., 2020; Poorter et al., 2015; Stegen et al., 2011). The summary highlights the critical significance of topography in temperate forests in evaluating the interactions of topography, climate, and soil in promoting stand structure diversity and aboveground biomass output. To support sustainable forest management practices, the study emphasizes the need for more research, especially on the effects of climate change and the connections between soil qualities and forest structure and function. The present study provides a synthesis of the literature that clarifies the interdependent effects of soil, topography, and climate on aboveground biomass in forest ecosystems. It acknowledges the varying impacts of these factors at different scales and highlights the need for additional research to bridge the knowledge gaps that currently exist.

Relationship between, stand structure diversity, and aboveground biomass in single and multi-species forests

The current study provides a comprehensive examination of factors influencing aboveground biomass in forest ecosystems, with a focus on stand structure diversity, species composition, topography, soil, and climate. Drawing upon a synthesis of existing literature and regional-level experimental studies, the findings contribute valuable insights into the complex interplay of these factors. Firstly, the study emphasizes the positive correlation between stand structure diversity and aboveground biomass, irrespective of forest types or species composition. Notably, the role of species diversity is found to be negligible in influencing aboveground biomass. This aligns with established knowledge that stand structure diversity significantly contributes to aboveground biomass production in natural forest ecosystems (Ali et al. 2023; Wang et al. 2011). The study further explores the comparative impact of single-species and multi-species forests on aboveground biomass. Contrary to the general trend observed in the literature, which suggests higher biomass production in multi-species forests, the study reveals that the relationship is contingent upon soil and climatic conditions at specific forest sites. The diversity of the forest and stem density, influenced by soil and climate, emerge as critical factors driving aboveground biomass in both forest types (Schuler et al. 2017). Topography, including elevation, slope angle, latitude, and longitude, is identified as a key determinant of stand structure diversity and, consequently, aboveground biomass. The study unveils a positive relationship between topography and aboveground biomass in both single-species and multi-species forests, except in cases where slope angle negatively affects biomass productivity in single-species forests. The influence of slope angle is attributed to the mountainous ecosystem, where higher angles correlate with decreased aboveground biomass due to the challenging terrain. The synthesis of ecological theories and regional-level experiments aligns with the study's hypothesis that soil and climate primarily determine aboveground biomass in both forest types. Climatic conditions, especially precipitation and water availability, emerge as crucial factors influencing forest diversity and aboveground biomass. Soil fertility is highlighted as a key determinant, with nutrient-rich soils positively correlating with higher aboveground biomass. The findings challenge the traditional emphasis on species diversity as a driver of biomass, underscoring the significance of abiotic factors in shaping forest productivity. Importantly, the study answers research questions regarding the influence of climatic factors on aboveground biomass. Precipitation and relative humidity are identified as positive contributors to biomass, while temperature and wind pressure negatively impact aboveground biomass. The study underscores the predominant role of climate over forest diversity in controlling aboveground biomass productivity. In conclusion, the current research enhances our understanding of the nuanced relationships between stand structure diversity, species composition, topography, soil, and climate in determining aboveground biomass in forest ecosystems. By challenging established notions and emphasizing the intricate interplay of abiotic factors, the study provides valuable insights into sustainable forest management and underscores the need for continued research in this domain.

The role of big trees in the natural forest ecosystem of Pakistan

This comprehensive study delves into the complex interplay between big trees and forest ecosystems, specifically examining their impact on aboveground biomass and the dynamics of remaining trees in various forest types. The findings underscore the crucial role of environmental factors, such as soil fertility, temperature, and precipitation, in shaping the distribution and growth of big trees. Notably, the positive correlation between soil fertility and the prevalence of big trees reveals that nutrient-rich environments foster their growth, contributing to increased aboveground biomass productivity (Baker et al., 2009). Conversely, forests on nutrient-deficient sites, including sub-tropical thorn, sub-tropical broad-leaved, dry temperate *Quercus*, and dry temperate pure *Pinus gerardiana* forests, exhibit a scarcity of big trees due to environmental limitations. Moist temperate mixed and dry temperate conifer forests in the inner valleys of the Himalayas and the Hindu Kush Mountains emerge as favorable habitats for big trees, showcasing substantial growth in both size and height. However, the dominance of big trees in these areas limits the availability of resources for smaller trees, leading to a scarcity of understory and sub-canopy vegetation. The study emphasizes the prolonged maturation period of large-diameter trees, making them susceptible to global environmental shifts compared to understorey and sub-canopy trees. This vulnerability is attributed to direct exposure to climatic elements such as relative air humidity, solar radiation, wind strength, and temperature fluctuations (Bennett et al. 2015). While big trees play a pivotal role in aboveground biomass productivity, their dominance poses challenges to remaining trees and sub-canopy vegetation (Ali et al., 2018). The Community-Weighted Mean (CWM) of big trees emerges as a significant factor influencing aboveground biomass, particularly in remaining trees. The positive feedback loop between the understorey stratum and CWM contributes to higher aboveground biomass, aligning with prior research (Ali and Yan 2017). Interestingly, an increase in Shannon's species diversity is associated with a decrease in aboveground biomass, suggesting potential competitive exclusion in natural forest ecosystems (Yuan et al. 2012). However, taxonomic diversity proves to be beneficial, enhancing aboveground biomass in forests with large trees, irrespective of species richness and composition in the remaining tree population (Bastin et al. 2018). The study highlights the nuanced relationships between big trees and forest dynamics, emphasizing their ecological significance and the intricate factors influencing their growth. The findings contribute valuable insights into forest management strategies, particularly in regions like Pakistani forests, where harsh climatic and soil conditions favor the contribution of medium and small trees over their larger counterparts (Ali et al. 2016).

The role of multiple biotic and abiotic drivers of aboveground biomass in the natural forest ecosystem of Pakistan

This comprehensive study delves into the intricate dynamics influencing aboveground biomass across different strata (overstorey, understorey, and whole community) in the natural forest ecosystems of Pakistan. The research explores the interplay of various biotic and abiotic factors, emphasizing soil physiochemical properties, climate, and diverse biotic determinants.

In the whole community stratum, soil physiochemical factors, particularly clay loam-dominated composition, and elevated nutrient levels, exhibit a positive correlation with aboveground biomass (Li et al. 2019). Biotic determinants such as Shannon diversity, community-weighted traits, stand structure diversity, and the prevalence of big trees significantly contribute to aboveground biomass productivity (Ali & Yan 2017; Fotis et al. 2017). Conversely, soil macronutrients negatively impact biotic determinants, highlighting their role in shaping plant strategies, especially in nutrient-poor soils (Bartels & Chen 2010). Climatic variables, particularly mean precipitation, play a substantial role in enhancing biotic determinants and overall aboveground biomass productivity. The overstorey stratum reveals a positive feedback loop between soil physiochemical properties, notably clay loam-dominated soil with rich nutrient content, and aboveground biomass (Zhang et al. 2017). Biotic determinants, including Shannon diversity, community-weighted traits, and the prevalence of big trees, contribute significantly to aboveground biomass. However, big trees exhibit an adverse effect on Shannon's diversity and community-weighted traits (CWM), dominating fertile soil conditions (Bartels & Chen 2010). Soil macronutrients negatively impact the biotic determinants, leading to a decline in aboveground biomass productivity. Climatic variables, such as precipitation and temperature, positively influence aboveground biomass in this stratum. In the understorey stratum, soil physiochemical factors, excluding macronutrients, positively correlate with aboveground biomass. Biotic determinants, including Shannon diversity, community-weighted traits, and the presence of big trees, contribute significantly to aboveground biomass productivity (Ali & Yan 2017). However, big trees exert a negative influence on Shannon diversity and community-weighted traits, reducing overall aboveground biomass productivity. The study underscores the species complementarity effect in low-nutrient soils within the understorey. Climatic variables particularly mean precipitation and temperature; positively influence biotic determinants and overall aboveground biomass productivity. This study collectively highlights the intricate relationships between soil properties, climate, and various biotic determinants in shaping aboveground biomass across different strata in Pakistani forest ecosystems. It emphasizes the pivotal role of large trees in driving aboveground biomass, the contrasting impacts of soil macronutrients, and the nuanced interplay between climatic variables and biotic factors. The findings contribute to a deeper understanding of forest dynamics and provide insights into sustainable forest management practices.

The carbon sequestration and its biotic and abiotic determinants in different forest ecosystems of Pakistan

The study delves into the intricate relationship between topography and carbon sequestration across diverse forest types in Pakistan. Contrary to a general trend where higher elevations are associated with reduced carbon sequestration due to cooler temperatures and limited water availability, the dry temperate conifer forest stands out. In this unique case, an increase in elevation correlates with enhanced carbon sequestration, possibly attributed to the specific geography and vegetation quality up to a certain limit (Luo JJ, et al., 2005). This emphasizes the context-dependent nature of elevation effects on carbon dynamics in mountainous regions, challenging simplistic assumptions. Biotic variables, such as stand structure diversity and species richness, play crucial roles in influencing carbon sequestration. Larger tree diameters and heights positively correlate with increased carbon sequestration, aligning with the established understanding of mature trees contributing significantly to carbon storage. However, a noteworthy finding challenges conventional wisdom the negative correlation between carbon sequestration and species richness. This implies that, in the examined ecosystems, factors like tree height and diameter at breast height exert more influence on carbon sequestration than species richness, challenging prevailing notions regarding biodiversity's direct positive impact on carbon storage (Sharma et al., 2016; Ali et al., 2023). The study underscores the substantial impact of soil physicochemical properties on carbon sequestration. Increased soil fertility, driven by factors like clay loam content and macronutrients, positively correlates with higher carbon sequestration. The analysis further identifies specific soil factors influencing carbon sequestration in each forest type, highlighting the nuanced relationships between soil characteristics and carbon storage (Li et al., 2013; Sanaei et al., 2018). Additionally, the study reveals the differential effects of micronutrients, with copper enhancing carbon sequestration and others such as nickel, manganese, and chromium leading to a decline, emphasizing the importance of considering micronutrient dynamics in carbon sequestration models (Ali et al., 2022). Climate emerges as a major determinant of carbon sequestration across diverse forest types. Generally, increased precipitation, temperature, relative humidity, and wind pressure positively influence carbon sequestration. However, the dry temperate pure *Pinus gerardiana* forest presents a unique scenario where precipitation and temperature lead to a decline in carbon sequestration. This finding underscores the need for a nuanced understanding of specific climatic conditions, as different ecosystems may respond uniquely to climate variables. The study emphasizes that, in harsh climatic conditions, carbon sequestration is primarily dependent on soil-related factors such as clay loam content and nutrient levels (Ali et al., 2023; Ali et al., 2019b; Körner, 2007). It becomes evident that carbon sequestration is a complex interplay of multiple factors within distinct forest ecosystems. The intricate relationships between topography, biotic variables, soil properties, and climate contribute to the nuanced carbon dynamics observed across different forest types in Pakistan. The study challenges simplistic generalizations, highlighting the need for region-specific considerations in understanding and managing carbon sequestration. By providing detailed insights into the specific drivers of carbon storage in each forest type, the research contributes valuable information for policymakers and conservationists working towards sustainable forest management and climate change mitigation.

Conclusion

In the intricate ecosystems of Pakistani forests, this comprehensive study reveals that aboveground biomass and carbon sequestration are profoundly influenced by the dynamic interplay of climatic and soil conditions, topography, and stand structure diversity across various strata. Favorable climatic conditions, including higher precipitation and moderate temperatures, coupled with nutrient-rich soils (clay loam-dominated with ample carbon, nitrogen, phosphorous, and micronutrients); significantly contribute to increased aboveground biomass. Topography and stand structure diversity play pivotal roles in creating an environment conducive to sustained tree growth, contributing to higher aboveground biomass. The study establishes that both single and multi-species forests respond to similar principles in terms of aboveground biomass dynamics. The study underscores the facilitative role of stand structure diversity, particularly Shannon diversity, in enhancing aboveground biomass productivity. Both overstorey and understory diversity positively contribute to biomass, indicating a complex yet interconnected relationship. Climatic and soil conditions crucially impact the presence of big trees, positively contributing to aboveground biomass but also leading to a decline in the remaining trees. Some topographically isolated forests host a majority of big trees, limiting growth for the remaining trees. Biotic variables such as stand structure diversity and community-weighted traits mean, driven by climatic and soil factors, are identified as key determinants across forest types. The study demonstrates that abiotic variables, such as soil composition and climate, interact with biotic determinants, influencing aboveground biomass. Soil micronutrients, except macronutrients, and precipitation are highlighted as major contributors to biomass productivity, while soil macronutrients, wind pressure, and relative humidity have adverse effects. Carbon sequestration is predominantly governed by climatic factors, with temperature, precipitation, relative humidity, and wind pressure playing substantial roles. Soil characteristics, especially in harsh climates, significantly contribute to carbon sequestration. This study provides a detailed exploration of the intricate relationships governing aboveground biomass and carbon sequestration in Pakistani forests. The synthesized findings contribute valuable insights for policymakers, researchers, and conservationists aiming to develop targeted strategies for sustainable forest management and biodiversity conservation.

Recommendation

Based on the comprehensive findings of this study on Pakistani forests, several recommendations can be made to guide policymakers, researchers, and conservationists toward sustainable forest management and biodiversity conservation.

- Implement climate-smart forest management practices that consider the profound impact of climatic conditions on aboveground biomass and carbon sequestration.
- Develop adaptive strategies to cope with changing climatic conditions, emphasizing resilience and sustainability.
- Prioritize soil conservation efforts, especially in areas with nutrient-rich soils, to ensure the maintenance of favorable conditions for increased aboveground biomass.
- Implement nutrient management practices to address soil macronutrient imbalances, considering their adverse effects on biomass productivity.
- Develop and implement policies that promote the facilitative role of stand structure diversity, particularly Shannon diversity, in sustaining and increasing aboveground biomass.
- Implement measures to conserve big trees, recognizing their positive contribution to aboveground biomass.
- Develop strategies to address the potential decline in remaining trees associated with the presence of big trees, particularly in topographically isolated forests.
- Involve local communities in forest management and conservation efforts, considering their role in the sustainable use of forest resources.
- Conduct educational programs to raise awareness about the interconnected relationships between climate, soil, diversity, and biomass, fostering a sense of responsibility for forest conservation.
- Develop integrated forest management plans that consider the dynamic interplay of biotic and abiotic factors influencing aboveground biomass and carbon sequestration.
- Prioritize landscape-level planning to address the complex relationships across various forest types and strata.
- Establish a comprehensive monitoring system to assess the effectiveness of implemented management strategies over time.

- Encourage continued research to further understand the nuanced relationships between different variables influencing forest ecosystems, contributing to adaptive management strategies.
- Integrate the study's findings into existing and future forest management policies to ensure alignment with scientific knowledge and sustainable practices.
- Foster collaboration between researchers, policymakers, and practitioners to enhance the effectiveness of conservation and management initiatives.

By incorporating these recommendations, stakeholders can work toward maintaining the health and productivity of Pakistani forests while promoting biodiversity conservation and sustainable resource use.

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Appendix 1 Summary relationship of the linear SEM for founding the relationship amongst AGB, SD, SSD, clay loam, CNP, and Topography in different forest types of Pakistan (Figure 18 A).

Response	Predictor	ß-Value	Std.Err	z-value	P-Value
AGB	SD	0.046**	0.018	2.594	0.009
AGB	SSD	0.012	0.02	0.572	0.567
AGB	Clay loam	0.02	0.013	1.523	0.128
AGB	CNP	0.073***	0.015	4.735	0.000
AGB	Topography	0.047**	0.016	3.005	0.003
SD	Clay loam	0.139**	0.051	2.747	0.006
SD	CNP	0.279***	0.058	4.777	0.000
SD	Topography	-0.428	0.055	-7.857	0.000
SSD	Clay loam	0.049	0.044	1.097	0.273
SSD	CNP	0.153**	0.05	3.047	0.002
SSD	Topography	0.138**	0.047	2.936	0.003
Clay loam	Topography	-0.004	0.075	-0.049	0.961
CNP	Topography	0.501***	0.061	8.198	0.000
Chisq	**p-value**	**gfi**	**Cfi**	**srmr**	**Aic**
4.520	0.003	0.991	0.092	0.023	1662.676

Appendix 2 Summary of direct and indirect relationship amongst AGB, SD, SSD, Clay loam, CNP, and Topography in different forest types of Pakistan (Figure 18 A).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.Iv	std.all
AGB	~	SD	0.046	0.018	2.594	0.009	0.011	0.081	0.04	0.17
AGB	~	SSD	0.012	0.02	0.572	0.567	-0.028	0.051	0.01	0.03
AGB	~	Clay loam	0.02	0.013	1.523	0.128	-0.006	0.045	0.02	0.09
AGB	~	CNP	0.073	0.015	4.735	0.000	0.043	0.103	0.07	0.35
AGB	~	Topography	0.047	0.016	3.005	0.003	0.016	0.078	0.04	0.22
SD	~	Clay loam	0.139	0.051	2.747	0.006	0.04	0.238	0.13	0.17
SD	~	CNP	0.279	0.058	4.777	0.000	0.165	0.394	0.27	0.36
SD	~	Topography	-0.428	0.055	-7.857	0.000	-0.535	-0.321	-0.42	-0.55
SSD	~	Clay loam	0.049	0.044	1.097	0.273	-0.038	0.136	0.04	0.07
SSD	~	CNP	0.153	0.05	3.047	0.002	0.055	0.252	0.15	0.24
SSD	~	Topography	0.138	0.047	2.936	0.003	0.046	0.23	0.13	0.21
Clay loam	~	Topography	-0.004	0.075	-0.049	0.961	-0.15	0.143	-0.00	-0.00
CNP	~	Topography	0.501	0.061	8.198	0.000	0.382	0.621	0.50	0.50
AGB	~~	AGB	0.027	0.003	10	0.000	0.021	0.032	0.02	0.63
SD	~~	SD	0.424	0.042	10	0.000	0.341	0.508	0.42	0.71
SSD	~~	SSD	0.328	0.033	10	0.000	0.264	0.392	0.32	0.81
Clay loam	~~	Clay loam	0.833	0.083	10	0.000	0.67	0.996	0.83	0.83
CNP	~~	CNP	0.745	0.074	10	0.000	0.599	0.891	0.74	0.74

Topography	~~	Topography	0.995	0	NA	NA	0.995	0.995	0.99	1
AGB	r2	AGB	0.366	NA	NA	NA	NA	NA	NA	NA
SD	r2	SD	0.29	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.185	NA	NA	NA	NA	NA	NA	NA
Clay loam	r2	Clay loam	0.163	NA	NA	NA	NA	NA	NA	NA
CNP	r2	CNP	0.251	NA	NA	NA	NA	NA	NA	NA

Appendix 3 Summary relationship of the linear SEM for founding the relationship amongst AGB, SD, SSD, SmP, SMP, and Topography in different forest types of Pakistan. Figure 18 B.

Response	**Predictor**	**ß-Value**	**Std.Err**	**z-value**	**P-Value**
AGB ~	SD	0.074	0.016	4.487	0.000
AGB ~	SSD	0.015	0.02	0.749	0.454
AGB ~	SmP	0.033	0.012	2.832	0.005
AGB ~	SMP	0.056	0.013	4.441	0.000
AGB ~	Topoghraphy	0.081	0.014	5.927	0.000
SD ~	SSD	0.245	0.086	2.834	0.005
SD ~	SmP	0.026	0.051	0.522	0.602
SD ~	SMP	0.126	0.053	2.362	0.018
SD ~	Topoghraphy	-0.313	0.055	-5.702	0.000
SSD ~	SmP	0.034	0.041	0.822	0.411
SSD ~	SMP	0.126	0.043	2.938	0.003
SSD ~	Topoghraphy	0.195	0.043	4.558	0.000
SmP ~	SMP	-0.091	0.073	-1.254	0.21
SmP ~	**Topoghraphy**	**-0.061**	**0.073**	**-0.838**	**0.402**
SMP ~	Topoghraphy	0.259	0.068	3.796	0.000

Appendix 4 Summary of direct and indirect relationship amongst AGB, SD, SSD, Clay loam, CNP, and Topography in different forest types of Pakistan. (Figure 18 B).

Response	**OP**	**Predictor**	**ß-Value**	**SE**	**Z-Value**	**P-value**	**Ci.lower**	**Ci.upper**	**std.Iv**	**std.all**
AGB	~	SD	0.074	0.016	4.487	0.000	0.042	0.106	0.074	0.278
AGB	~	SSD	0.015	0.02	0.749	0.454	-0.025	0.056	0.015	0.048
AGB	~	SmP	0.033	0.012	2.832	0.005	0.01	0.057	0.033	0.163
AGB	~	SMP	0.056	0.013	4.441	0.000	0.031	0.081	0.056	0.272
AGB	~	Topography	0.081	0.014	5.927	0.000	0.054	0.108	0.081	0.396
SD	~	SSD	0.245	0.086	2.834	0.005	0.076	0.414	0.245	0.201
SD	~	SmP	0.026	0.051	0.522	0.602	-0.073	0.126	0.026	0.034
SD	~	SMP	0.126	0.053	2.362	0.018	0.021	0.231	0.126	0.163
SD	~	Topography	-0.31	0.055	-5.70	0.000	-0.42	-0.205	-0.313	-0.403

SSD	~	SmP	0.034	0.041	0.822	0.411	-0.047	0.115	0.034	0.054
SSD	~	SMP	0.126	0.043	2.938	0.003	0.042	0.209	0.126	0.198
SSD	~	Topography	0.195	0.043	4.558	0	0.111	0.278	0.195	0.306
SmP	~	SMP	-0.09	0.073	-1.25	0.21	-0.234	0.051	-0.09	-0.091
SmP	~	Topography	-0.06	0.073	-0.83	0.402	-0.203	0.082	-0.06	-0.061
SMP	~	Topography	0.259	0.068	3.796	0	0.125	0.393	0.259	0.259
AGB	~~	AGB	0.027	0.003	10	0	0.022	0.033	0.027	0.648
SD	~~	SD	0.503	0.05	10	0	0.405	0.602	0.503	0.842
SSD	~~	SSD	0.337	0.034	10	0	0.271	0.403	0.337	0.838
SmP	~~	SmP	0.98	0.098	10	0	0.788	1.172	0.98	0.985
SMP	~~	SMP	0.928	0.093	10	0	0.746	1.11	0.928	0.933
Topoghraphy	~~	Topography	0.995	0	NA	NA	0.995	0.995	0.995	1
AGB	r2	AGB	0.352	NA	NA	NA	NA	NA	NA	NA
SD	r2	SD	0.158	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.162	NA	NA	NA	NA	NA	NA	NA
SmP	r2	SmP	0.015	NA	NA	NA	NA	NA	NA	NA
SMP	r2	SMP	0.067	NA	NA	NA	NA	NA	NA	NA

Appendix 5 Summary relationship of the linear SEM for founding the relationship amongst AGB, SD, SSD, Mt, MP, and Topography in different forest types of Pakistan (Figure 19 A).

Response	Predictor	ß-Value	Std.Err	z-value	P-Value
AGB	SD	0.086***	0.017	5.008	0.000
AGB	SSD	0.04	0.023	1.754	0.079
AGB	Mt	0.018	0.024	0.767	0.443
AGB	MP	0.03**	0.019	0.327	0.004
AGB	Topography	0.108***	0.02	5.317	0.000
SD	SSD	0.303**	0.091	3.335	0.001
SD	Mt	0.051	0.098	0.521	0.602
SD	MP	0.012	0.077	0.158	0.874
SD	Topography	-0.261	0.081	-3.211	0.001
SSD	Mt	-0.311	0.073	-4.245	0.000
SSD	MP	0.001	0.06	0.008	0.993
SSD	Topography	-0.018	0.063	-0.285	0.776
Mt	Topography	-0.568	0.046	-12.249	0.000
MP	Topography	0.519***	0.054	9.569	0.000
Chisq	**p-value**	**gfi**	**cfi**	**srmr**	**Aic**
6.023	0.028	0.088	0.990	0.0450	1463.609

Appendix 6 Summary of direct and indirect relationship amongst AGB, SD, SSD, Mt, MP, and Topography in different forest types of Pakistan (Figure 19 A).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.Iv	std.all
AGB	~	SD	0.086	0.017	5.008	0.000	0.052	0.12	0.086	0.324
AGB	~	SSD	0.04	0.023	1.754	0.079	-0.005	0.084	0.04	0.123
AGB	~	Mt	0.018	0.024	0.767	0.443	-0.028	0.065	0.018	0.089
AGB	~	MP	0.03	0.019	0.327	0.004	-0.043	0.03	-0.00	-0.027
AGB	~	Topoghraphy	0.108	0.02	5.317	0.000	0.068	0.147	0.108	0.525
SD	~	SSD	0.303	0.091	3.335	0.001	0.125	0.48	0.303	0.248
SD	~	Mt	0.051	0.098	0.521	0.602	-0.141	0.243	0.051	0.066
SD	~	MP	0.012	0.077	0.158	0.874	-0.138	0.162	0.012	0.015
SD	~	Topoghraphy	-0.261	0.081	-3.211	0.001	-0.421	-0.102	-0.26	-0.337
SSD	~	Mt	-0.311	0.073	-4.245	0	-0.454	-0.167	-0.31	-0.489
SSD	~	MP	0.001	0.06	0.008	0.993	-0.117	0.118	0.001	0.001
SSD	~	Topoghraphy	-0.018	0.063	-0.285	0.776	-0.142	0.106	-0.01	-0.028
Mt	~	MP	-0.408	0.05	-8.137	0	-0.506	-0.309	-0.40	-0.377
Mt	~	Topoghraphy	-0.568	0.046	-12.24	0	-0.659	-0.477	-0.56	-0.568
MP	~	Topoghraphy	0.519	0.054	9.569	0	0.412	0.625	0.519	0.56
AGB	~~	AGB	0.03	0.003	10	0	0.024	0.036	0.03	0.725
SD	~~	SD	0.517	0.052	10	0	0.416	0.618	0.517	0.864
SSD	~~	SSD	0.314	0.031	10	0	0.253	0.376	0.314	0.782
Mt	~~	Mt	0.293	0.029	10	0	0.236	0.351	0.293	0.295
MP	~~	MP	0.585	0.058	10	0	0.47	0.7	0.585	0.686
Topoghraphy	~~	Topoghraphy	0.995	0	NA	NA	0.995	0.995	0.995	1
AGB	r2	AGB	0.275	NA	NA	NA	NA	NA	NA	NA
SD	r2	SD	0.136	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.218	NA	NA	NA	NA	NA	NA	NA
Mt	r2	Mt	0.705	NA	NA	NA	NA	NA	NA	NA
MP	r2	MP	0.314	NA	NA	NA	NA	NA	NA	NA

Appendix 7 Summary relationship of the linear SEM for founding the relationship amongst AGB, SD, SSD, MRH, MWP, and Topoghrphy in different forest types of Pakistan (Figure 19 B).

Response	Predictor	ß-Value	Std.Err	z-value	P-Value
AGB	SD	0.085	0.018	4.745	0.000
AGB	SSD	0.029	0.023	1.27	0.204
AGB	MRH	0.04	0.021	0.18	0.857
AGB	MWP	-0.02	0.022	-0.089	0.929
AGB	Topoghraphy	0.091	0.018	5.202	0.000
SD	SSD	0.133	0.091	1.459	0.144
SD	MRH	0.275	0.08	3.435	0.001
SD	MWP	0.095	0.087	1.089	0.276

SD	Topoghraphy	-0.236	0.067	-3.511	0.000
SSD	MRH	0.337	0.058	5.856	0.000
SSD	MWP	0.159	0.067	2.383	0.017
SSD	Topoghraphy	0.272	0.049	5.603	0.000
MRH	MWP	-0.865	0.054	-15.883	0.000
MRH	Topoghraphy	-0.343	0.054	-6.3	0,000
MWP	Topoghraphy	-0.511	0.061	-8.406	0.000

Appendix 8 Summary of direct and indirect relationship amongst AGB, SD, SSD, Mt, MP, and Topography in different forest types of Pakistan (Figure 19 B).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.lv	std.all
AGB	~	SD	0.085	0.018	4.745	0	0.05	0.12	0.085	0.321
AGB	~	SSD	0.029	0.023	1.27	0.204	-0.016	0.075	0.029	0.091
AGB	~	MRH	0.004	0.021	0.18	0.857	-0.037	0.045	0.004	0.018
AGB	~	MWP	-0.002	0.022	-0.08	0.929	-0.045	0.041	-0.00	-0.01
AGB	~	Topoghraphy	0.091	0.018	5.202	0	0.057	0.125	0.091	0.443
SD	~	MRH	0.275	0.08	3.435	0.001	0.118	0.432	0.275	0.355
SD	~	MWP	0.095	0.087	1.089	0.276	-0.076	0.265	0.095	0.122
SD	~	Topoghraphy	-0.236	0.067	-3.51	0	-0.367	-0.104	-0.23	-0.304
SSD	~	MRH	0.337	0.058	5.856	0	0.225	0.45	0.337	0.531
SSD	~	MWP	0.159	0.067	2.383	0.017	0.028	0.29	0.159	0.25
SSD	~	Topoghraphy	0.272	0.049	5.603	0	0.177	0.367	0.272	0.428
MRH	~	Topoghraphy	-0.343	0.054	-6.3	0	-0.45	-0.236	-0.34	-0.343
MWP	~	Topoghraphy	-0.511	0.061	-8.40	0	-0.63	-0.392	-0.51	-0.511
AGB	~~	AGB	0.031	0.003	10	0	0.025	0.037	0.031	0.729
SD	~~	SD	0.478	0.048	10	0	0.384	0.572	0.478	0.799
SSD	~~	SSD	0.289	0.029	10	0	0.233	0.346	0.289	0.72
Topoghraphy	~~	Topoghraphy	0.995	0	NA	NA	0.995	0.995	0.995	1
AGB	r2	AGB	0.271	NA	NA	NA	NA	NA	NA	NA
SD	r2	SD	0.201	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.28	NA	NA	NA	NA	NA	NA	NA
MRH	r2	MRH	0.562	NA	NA	NA	NA	NA	NA	NA
MWP	r2	MWP	0.261	NA	NA	NA	NA	NA	NA	NA

Appendix 9 Summary relationship of the linear SEM for founding the relationship amongst OAGB, UAGB, OSD, USD, OSSD, USSD, clay SmP, and SMP in different forest types of Pakistan (Figure 20 A).

Response	Predictor	ß-Value	Std.Err	z-value	P-Value
OAGB	UAGB	0.051	0.108	0.473	0.636
OAGB	OSD	-0.056	0.071	-0.789	0.43
OAGB	USD	0.1	0.079	1.253	0.21
OAGB	OSSD	0.543***	0.065	8.318	0
OAGB	USSD	-0.118	0.104	-1.134	0.257
OAGB	SmP	0.115	0.065	1.768	0.077
OAGB	SMP	-0.026	0.063	-0.412	0.68
UAGB	OSD	0.111*	0.046	2.436	0.015
UAGB	USD	0.116*	0.051	2.252	0.024
UAGB	OSSD	-0.085	0.042	-2.005	0.045
UAGB	USSD	0.678***	0.048	14.025	0
UAGB	SmP	0.064	0.042	1.505	0.132
UAGB	SMP	0.115**	0.04	2.855	0.004
OSD	OSSD	0.204**	0.064	3.195	0.001
OSD	USSD	0.09	0.075	1.201	0.23
OSD	SmP	-0.075	0.065	-1.154	0.248
OSD	SMP	0.058	0.062	0.924	0.355
USD	OSSD	0.014	0.06	0.237	0.812
USD	USSD	0.583***	0.057	10.276	0
USD	SmP	0.026	0.061	0.424	0.672
USD	SMP	0.08	0.058	1.374	0.17
OSSD	SmP	0.046	0.072	0.633	0.526
OSSD	SMP	-0.115	0.068	-1.676	0.094
USSD	SmP	-0.038	0.077	-0.496	0.62
USSD	SMP	0.026	0.072	0.359	0.72
SmP	SMP	0.14*	0.066	2.108	0.035

Appendix 10 Summary of direct and indirect relationship amongst OAGB, UAGB, OSD, USD, OSSD, USSD, SmP, and SMP in different forest types of Pakistan (Figure 20 A).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.Iv	std.all
OAGB	~	UAGB	0.051	0.108	0.473	0.636	-0.161	0.264	0.051	0.051
OAGB	~	OSD	-0.05	0.071	-0.789	0.43	-0.195	0.083	-0.05	-0.112
OAGB	~	USD	0.1	0.079	1.253	0.21	-0.056	0.255	0.1	0.099
OAGB	~	OSSD	0.543	0.065	8.318	0.000	0.415	0.671	0.543	0.541
OAGB	~	USSD	-0.11	0.104	-1.134	0.257	-0.322	0.086	-0.11	-0.236
OAGB	~	SmP	0.115	0.065	1.768	0.077	-0.012	0.242	0.115	0.115
OAGB	~	SMP	-0.02	0.063	-0.412	0.68	-0.149	0.097	-0.02	-0.052
UAGB	~	OSD	0.111	0.046	2.436	0.015	0.022	0.201	0.111	0.111
UAGB	~	USD	0.116	0.051	2.252	0.024	0.015	0.216	0.116	0.115
UAGB	~	OSSD	-0.08	0.042	-2.005	0.045	-0.168	-0.002	-0.08	-0.17
UAGB	~	USSD	0.678	0.048	14.025	0.000	0.583	0.773	0.678	0.678
UAGB	~	SmP	0.064	0.042	1.505	0.132	-0.019	0.146	0.064	0.064
UAGB	~	SMP	0.115	0.04	2.855	0.004	0.036	0.194	0.115	0.115
OSD	~	OSSD	0.204	0.064	3.195	0.001	0.079	0.33	0.204	0.204
OSD	~	USSD	0.09	0.075	1.201	0.23	-0.057	0.236	0.09	0.09
OSD	~	SmP	-0.07	0.065	-1.154	0.248	-0.203	0.053	-0.07	-0.15
OSD	~	SMP	0.058	0.062	0.924	0.355	-0.065	0.18	0.058	0.057
USD	~	OSSD	0.014	0.06	0.237	0.812	-0.104	0.132	0.014	0.014
USD	~	USSD	0.583	0.057	10.276	0.000	0.472	0.694	0.583	0.584
USD	~	SmP	0.026	0.061	0.424	0.672	-0.094	0.146	0.026	0.026
USD	~	SMP	0.08	0.058	1.374	0.17	-0.034	0.195	0.08	0.08
OSSD	~	SmP	0.046	0.072	0.633	0.526	-0.096	0.187	0.046	0.046
OSSD	~	SMP	-0.11	0.068	-1.676	0.094	-0.249	0.019	-0.11	-0.228
OSSD	~	SmP	-0.03	0.077	-0.496	0.62	-0.188	0.112	-0.03	-0.076
OSSD	~	SMP	0.026	0.072	0.359	0.72	-0.116	0.168	0.026	0.026
SmP	~	SMP	0.14	0.066	2.108	0.035	0.01	0.27	0.14	0.139
OAGB	~~	OAGB	0.694	0.07	9.975	0.000	0.557	0.83	0.694	0.694
UAGB	~~	UAGB	0.297	0.03	9.975	0.000	0.239	0.355	0.297	0.298
OSD	~~	OSD	0.715	0.072	9.975	0.000	0.574	0.855	0.715	0.715
USD	~~	USD	0.631	0.063	9.975	0.000	0.507	0.755	0.631	0.634
OSSD	~~	OSSD	0.877	0.088	9.975	0.000	0.705	1.05	0.877	0.883
USSD	~~	USSD	0.985	0.099	9.975	0.000	0.791	1.179	0.985	0.987
OAGB	r2	OAGB	0.306	NA	NA	NA	NA	NA	NA	NA
UAGB	r2	UAGB	0.702	NA	NA	NA	NA	NA	NA	NA
OSD	r2	OSD	0.285	NA	NA	NA	NA	NA	NA	NA
USD	r2	USD	0.366	NA	NA	NA	NA	NA	NA	NA
OSSD	r2	OSSD	0.117	NA	NA	NA	NA	NA	NA	NA

Appendix **11** Summary relationship of the linear SEM for founding the relationship amongst OAGB, UAGB, OSD, USD, OSSD, USSD, clay loam, and CNP in different forest types of Pakistan (Figure 20 B).

Response	**Predictor**	**ß-Value**	**Std.Err**	**z-value**	**P-Value**
OAGB	UAGB	0.062	0.106	0.586	0.558
OAGB	OSD	-0.096	0.074	-1.305	0.192
OAGB	USD	0.102	0.08	1.277	0.202
OAGB	OSSD	0.54	0.066	8.218	0
OAGB	USSD	-0.128	0.102	-1.244	0.213
OAGB	CNP	0.086	0.079	1.092	0.275
OAGB	Clay loam	0.03	0.065	0.466	0.641
UAGB	OSD	0.1	0.049	2.04	0.041
UAGB	USD	0.134	0.052	2.55	0.011
UAGB	OSSD	-0.099	0.043	-2.274	0.023
UAGB	USSD	0.668	0.049	13.512	0
UAGB	CNP	0.062	0.052	1.189	0.234
UAGB	Clay loam	-0.046	0.043	-1.062	0.288
OSD	USD	0.323	0.072	4.463	0
OSD	OSSD	0.145	0.062	2.342	0.019
OSD	USSD	0.089	0.071	1.252	0.21
OSD	CNP	0.31	0.073	4.259	0
OSD	Clay loam	0	0.062	-0.008	0.994
USD	OSSD	-0.015	0.061	-0.252	0.801
USD	USSD	0.574	0.057	10.104	0
USD	CNP	0.104	0.071	1.468	0.142
USD	Clay loam	0.03	0.061	0.486	0.627
OSSD	USSD	-0.048	0.066	-0.722	0.47
OSSD	CNP	0.174	0.082	2.131	0.033
OSSD	Clay loam	0.071	0.071	1.003	0.316
USSD	CNP	0.094	0.087	1.074	0.283
USSD	Clay loam	0.014	0.076	0.182	0.855
USSD	Clay loam	0.29	0.058	4.987	0
USSD	Topoghraphy	0.464	0.058	7.959	0

Appendix 12 Summary of direct and indirect relationship amongst QAGB, UAGB, OSD, USD, OSSD, USSD, SmP, and SMP in different forest types of Pakistan (Figure 20 B).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.Iv	std.all
OAGB	~	UAGB	0.062	0.106	0.586	0.558	-0.146	0.27	0.062	0.062
OAGB	~	OSD	-0.096	0.074	-1.305	0.192	-0.241	0.048	-0.096	-0.096
OAGB	~	USD	0.102	0.08	1.277	0.202	-0.054	0.258	0.102	0.101
OAGB	~	OSSD	0.54	0.066	8.218	0.000	0.411	0.669	0.54	0.538
OAGB	~	USSD	-0.128	0.102	-1.244	0.213	-0.328	0.073	-0.128	-0.127
OAGB	~	CNP	0.086	0.079	1.092	0.275	-0.068	0.24	0.086	0.086
OAGB	~	Clay loam	0.03	0.065	0.466	0.641	-0.096	0.157	0.03	0.03
UAGB	~	OSD	0.1	0.049	2.04	0.041	0.004	0.196	0.1	0.1
UAGB	~	USD	0.134	0.052	2.55	0.011	0.031	0.236	0.134	0.133
UAGB	~	OSSD	-0.099	0.043	-2.274	0.023	-0.184	-0.014	-0.099	-0.098
UAGB	~	USSD	0.668	0.049	13.512	0.000	0.571	0.765	0.668	0.668
UAGB	~	CNP	0.062	0.052	1.189	0.234	-0.04	0.165	0.062	0.062
UAGB	~	Clay loam	-0.046	0.043	-1.062	0.288	-0.13	0.039	-0.046	-0.046
OSD	~	USD	0.323	0.072	4.463	0.000	0.181	0.465	0.323	0.323
OSD	~	OSSD	0.145	0.062	2.342	0.019	0.024	0.267	0.145	0.145
OSD	~	USSD	0.089	0.071	1.252	0.21	-0.051	0.229	0.089	0.089
OSD	~	CNP	0.31	0.073	4.259	0.000	0.167	0.453	0.31	0.31
OSD	~	Clay loam	0	0.062	-0.008	0.994	-0.123	0.122	0	0
USD	~	OSSD	-0.015	0.061	-0.252	0.801	-0.134	0.104	-0.015	-0.015
USD	~	USSD	0.574	0.057	10.104	0.000	0.463	0.686	0.574	0.575
USD	~	CNP	0.104	0.071	1.468	0.142	-0.035	0.243	0.104	0.104
USD	~	Clay loam	0.03	0.061	0.486	0.627	-0.09	0.149	0.03	0.03
OSSD	~	USSD	-0.048	0.066	-0.722	0.47	-0.178	0.082	-0.048	-0.048
OSSD	~	CNP	0.174	0.082	2.131	0.033	0.014	0.335	0.174	0.175
OSSD	~	Clay loam	0.071	0.071	1.003	0.316	-0.068	0.211	0.071	0.071
USSD	~	CNP	0.094	0.087	1.074	0.283	-0.077	0.265	0.094	0.094
USSD	~	Clay loam	0.014	0.076	0.182	0.855	-0.135	0.163	0.014	0.014
CNP	~	Clay loam	0.29	0.058	4.987	0.000	0.176	0.404	0.29	0.29
OAGB	~~	OAGB	0.698	0.07	9.975	0.000	0.561	0.835	0.698	0.698
UAGB	~~	UAGB	0.312	0.031	9.975	0.000	0.251	0.373	0.312	0.313
OSD	~~	OSD	0.656	0.066	9.975	0.000	0.527	0.784	0.656	0.656
USD	~~	USD	0.628	0.063	9.975	0.000	0.505	0.751	0.628	0.631
OSSD	~~	OSSD	0.857	0.086	9.975	0.000	0.688	1.025	0.857	0.862
USSD	~~	USSD	0.979	0.098	9.975	0.000	0.787	1.172	0.979	0.982
CNP	~~	CNP	0.647	0.065	9.975	0.000	0.52	0.774	0.647	0.647
Clay loam	~~	Clay loam	0.959	0.096	9.975	0.000	0.771	1.148	0.959	0.96

OAGB	r2	OAGB	0.302	NA	NA	NA	NA	NA	NA	NA
UAGB	r2	UAGB	0.687	NA	NA	NA	NA	NA	NA	NA
OSD	r2	OSD	0.344	NA	NA	NA	NA	NA	NA	NA
USD	r2	USD	0.369	NA	NA	NA	NA	NA	NA	NA
OSSD	r2	OSSD	0.138	NA	NA	NA	NA	NA	NA	NA
USSD	r2	USSD	0.018	NA	NA	NA	NA	NA	NA	NA
CNP	r2	CNP	0.353	NA	NA	NA	NA	NA	NA	NA
Clay loam	r2	Clay loam	0.04	NA	NA	NA	NA	NA	NA	NA

Appendix 13 Summary relationship of the linear SEM for founding the relationship amongst QAGB, UAGB, OSD, USD, OSSD, USSD, Mt, and MP in different forest types of Pakistan (Figure 21 A).

Response	**Predictor**	**ß-Value**	**Std.Err**	**z-value**	**P-Value**
UAGB	OAGB	0.017	0.046	0.381	0.703
UAGB	USD	0.143	0.053	2.69	0.007
UAGB	OSD	0.09	0.045	1.997	0.046
UAGB	USSD	0.666	0.049	13.733	0
UAGB	OSSD	-0.078	0.05	-1.554	0.12
UAGB	Mt	0.223	0.059	3.763	0
UAGB	MP	0.204	0.062	3.311	0.001
OAGB	USD	0.128	0.082	1.571	0.116
OAGB	OSD	-0.076	0.069	-1.096	0.273
OAGB	USSD	-0.086	0.075	-1.154	0.249
OAGB	OSSD	0.571	0.066	8.594	0
OAGB	Mt	0.106	0.091	1.169	0.242
OAGB	MP	0.063	0.095	0.669	0.503
USD	USSD	0.437	0.057	7.673	0
USD	OSSD	-0.125	0.057	-2.198	0.028
USD	Mt	-0.145	0.078	-1.851	0.064
USD	MP	0.104	0.082	1.263	0.207
OSD	USSD	0.304	0.068	4.467	0
OSD	OSSD	0.159	0.071	2.255	0.024
OSD	Mt	0.313	0.096	3.269	0.001
OSD	MP	0.327	0.1	3.264	0.001
USSD	Mt	-0.034	0.1	-0.346	0.729
USSD	MP	0.304	0.102	2.974	0.003
OSSD	Mt	-0.456	0.091	-4.998	0
OSSD	MP	-0.145	0.099	-1.47	0.142

Appendix 1**114** Summary of direct and indirect relationship amongst OAGB, UAGB, OSD, USD, OSSD, USSD, Mt, and MP in different forest types of Pakistan (Figure 21 A).

Response	**OP**	**Predictor**	**ß-Value**	**SE**	**Z-Value**	**P-value**	**Ci.lower**	**Ci.upper**	**std.lv**	**std.all**
AGB	~	SD	0.086	0.017	5.008	0	0.052	0.12	0.086	0.324
AGB	~	SSD	0.04	0.023	1.754	0.079	-0.005	0.084	0.04	0.123
AGB	~	Mt	0.018	0.024	0.767	0.443	-0.028	0.065	0.018	0.089
AGB	~	MP	0.03	0.019	0.327	0.004	-0.043	0.03	-0.006	-0.027
AGB	~	Topoghraphy	0.108	0.02	5.317	0	0.068	0.147	0.108	0.525
SD	~	SSD	0.303	0.091	3.335	0.001	0.125	0.48	0.303	0.248
SD	~	Mt	0.051	0.098	0.521	0.602	-0.141	0.243	0.051	0.066
SD	~	MP	0.012	0.077	0.158	0.874	-0.138	0.162	0.012	0.015
SD	~	Topoghraphy	-0.261	0.081	-3.211	0.001	-0.421	-0.102	-0.261	-0.337
SSD	~	Mt	-0.311	0.073	-4.245	0	-0.454	-0.167	-0.311	-0.489
SSD	~	MP	0.001	0.06	0.008	0.993	-0.117	0.118	0.001	0.001
SSD	~	Topoghraphy	-0.018	0.063	-0.285	0.776	-0.142	0.106	-0.018	-0.028
Mt	~	MP	-0.408	0.05	-8.137	0	-0.506	-0.309	-0.408	-0.377
Mt	~	Topoghraphy	-0.568	0.046	-12.249	0	-0.659	-0.477	-0.568	-0.568
MP	~	Topoghraphy	0.519	0.054	9.569	0	0.412	0.625	0.519	0.56
AGB	~~	AGB	0.03	0.003	10	0	0.024	0.036	0.03	0.725
SD	~~	SD	0.517	0.052	10	0	0.416	0.618	0.517	0.864
SSD	~~	SSD	0.314	0.031	10	0	0.253	0.376	0.314	0.782
Mt	~~	Mt	0.293	0.029	10	0	0.236	0.351	0.293	0.295
MP	~~	MP	0.585	0.058	10	0	0.47	0.7	0.585	0.686
Topoghraphy	~~	Topoghraphy	0.995	0	NA	NA	0.995	0.995	0.995	1
AGB	r2	AGB	0.275	NA	NA	NA	NA	NA	NA	NA
SD	r2	SD	0.136	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.218	NA	NA	NA	NA	NA	NA	NA
Mt	r2	Mt	0.705	NA	NA	NA	NA	NA	NA	NA
MP	r2	MP	0.314	NA	NA	NA	NA	NA	NA	NA

Appendix 15 Summary relationship of the linear SEM for founding the relationship amongst OAGB, UAGB, OSD, USD, OSSD, USSD, Mt, and MP in different forest types of Pakistan (Figure 21 B).

Response	**Predictor**	**ß-Value**	**Std.Err**	**z-value**	**P-Value**
UAGB	OAGB	0.023	0.046	0.507	0.612
UAGB	USD	0.174	0.057	3.053	0.002
UAGB	OSD	0.179	0.046	3.878	0
UAGB	USSD	0.671	0.049	13.807	0
UAGB	OSSD	-0.105	0.049	-2.17	0.03
UAGB	MRH	-0.227	0.064	-3.531	0
UAGB	MWP	-0.148	0.054	-2.747	0.006
OAGB	USD	0.119	0.087	1.362	0.173
OAGB	OSD	-0.046	0.071	-0.644	0.52
OAGB	USSD	-0.089	0.075	-1.196	0.232
OAGB	OSSD	0.544	0.064	8.511	0
OAGB	MRH	-0.058	0.099	-0.584	0.559
OAGB	MWP	-0.052	0.083	-0.63	0.529
USD	USSD	0.379	0.054	6.955	0
USD	OSSD	-0.145	0.051	-2.848	0.004
USD	MRH	0.344	0.077	4.501	0
USD	MWP	-0.085	0.067	-1.266	0.206
OSD	USSD	0.144	0.067	2.158	0.031
OSD	OSSD	-0.02	0.063	-0.313	0.754
OSD	MRH	0.506	0.088	5.747	0
OSD	MWP	0.07	0.083	0.837	0.403
USSD	MRH	0.365	0.09	4.074	0
USSD	MWP	-0.104	0.088	-1.176	0.24
OSSD	MRH	0.222	0.095	2.34	0.019
OSSD	MWP	-0.031	0.095	-0.333	0.739

Appendix 16 Summary of direct and indirect relationship amongst OAGB, UAGB, OSD, USD, OSSD, USSD, MRH, and MWP in different forest types of Pakistan. (Figure 21 B).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.lv	std.all
UAGB	~	OAGB	0.023	0.04	0.50	0.612	-0.067	0.114	0.023	0.023
UAGB	~	USD	0.174	0.05	3.05	0.002	0.062	0.285	0.174	0.173
UAGB	~	OSD	0.179	0.04	3.87	0.000	0.089	0.27	0.179	0.179
UAGB	~	USSD	0.671	0.04	13.80	0.000	0.576	0.767	0.671	0.671
UAGB	~	OSSD	-0.10	0.04	-2.1	0.03	-0.2	-0.01	-0.105	-0.105
UAGB	~	MRH	-0.22	0.06	-3.53	0.000	-0.352	-0.101	-0.227	-0.226
UAGB	~	MWP	-0.14	0.05	-2.74	0.006	-0.254	-0.042	-0.148	-0.148
OAGB	~	USD	0.119	0.08	1.362	0.173	-0.052	0.289	0.119	0.118
OAGB	~	OSD	-0.04	0.07	-0.644	0.52	-0.185	0.093	-0.046	-0.046
OAGB	~	USSD	-0.08	0.07	-1.196	0.232	-0.235	0.057	-0.089	-0.089
OAGB	~	OSSD	0.544	0.06	8.511	0.000	0.419	0.669	0.544	0.542
OAGB	~	MRH	-0.058	0.09	-0.584	0.559	-0.251	0.136	-0.058	-0.057
OAGB	~	MWP	-0.052	0.08	-0.63	0.529	-0.215	0.11	-0.052	-0.052
USD	~	OSD	0.131	0.05	2.294	0.022	0.019	0.243	0.131	0.131
USD	~	USSD	0.379	0.05	6.955	0.000	0.272	0.485	0.379	0.379
USD	~	OSSD	-0.145	0.05	-2.848	0.004	-0.245	-0.045	-0.145	-0.145
USD	~	MRH	0.344	0.07	4.501	0.000	0.194	0.494	0.344	0.343
USD	~	MWP	-0.085	0.06	-1.266	0.206	-0.217	0.047	-0.085	-0.085
OSD	~	USSD	0.144	0.06	2.158	0.031	0.013	0.275	0.144	0.144
OSD	~	OSSD	-0.02	0.06	-0.313	0.754	-0.144	0.104	-0.02	-0.02
OSD	~	MRH	0.506	0.08	5.747	0.000	0.334	0.679	0.506	0.504
OSD	~	MWP	0.07	0.08	0.837	0.403	-0.094	0.233	0.07	0.07
USSD	~	OSSD	-0.174	0.06	-2.636	0.008	-0.303	-0.045	-0.174	-0.174
USSD	~	MRH	0.365	0.0	4.074	0.000	0.19	0.541	0.365	0.364
USSD	~	MWP	-0.104	0.08	-1.176	0.24	-0.276	0.069	-0.104	-0.104
OSSD	~	MRH	0.222	0.09	2.34	0.019	0.036	0.408	0.222	0.222
OSSD	~	MWP	-0.031	0.09	-0.333	0.739	-0.217	0.154	-0.031	-0.032
MRH	~	MWP	-0.686	0.05	-13.40	0.000	-0.786	-0.586	-0.686	-0.689
UAGB	~~	UAGB	0.298	0.0	9.975	0.000	0.239	0.356	0.298	0.298
OAGB	~~	OAGB	0.705	0.07	9.975	0.000	0.566	0.843	0.705	0.705
USD	~~	USD	0.467	0.04	9.975	0.000	0.375	0.559	0.467	0.469
OSD	~~	OSD	0.721	0.07	9.975	0.000	0.58	0.863	0.721	0.722
USSD	~~	USSD	0.81	0.08	9.975	0.000	0.651	0.97	0.81	0.812
OSSD	~~	OSSD	0.934	0.09	9.975	0.000	0.75	1.117	0.934	0.94
MRH	~~	MRH	0.52	0.05	9.975	0.000	0.418	0.622	0.52	0.526
MWP	~~	MWP	0.998	0	NA	NA	0.998	0.998	0.998	1
UAGB	r2	UAGB	0.702	NA	NA	NA	NA	NA	NA	NA
OAGB	r2	OAGB	0.295	NA	NA	NA	NA	NA	NA	NA
USD	r2	USD	0.531	NA	NA	NA	NA	NA	NA	NA
OSD	r2	OSD	0.278	NA	NA	NA	NA	NA	NA	NA
USSD	r2	USSD	0.188	NA	NA	NA	NA	NA	NA	NA
OSSD	r2	OSSD	0.06	NA	NA	NA	NA	NA	NA	NA
MRH	r2	MRH	0.474	NA	NA	NA	NA	NA	NA	NA

Appendix 17 Summary relationship of the linear SEM for founding the relationship amongst AGB, SSD, Clay loam, and CNP in single species forests of Pakistan (Figure 31 A).

Response	Predictor	ß-Value	Std. Err	z-value	P-Value
AGB	SSD	0.005	0.024	0.2	0.841
AGB	Clay loam	0.033	0.019	1.752	0.08
AGB	CNP	0.154	0.02	7.552	0
AGB	Topography	0.238	0.065	3.666	0
SSD	Clay loam	0.153	0.104	1.479	0.139
SSD	CNP	0.181	0.113	1.604	0.109
SSD	Topography	0.656	0.356	1.842	0.066
Clay loam	Topography	1.252	0.439	2.85	0.004
CNP	Topography	-0.817	0.396	-2.064	0.039
Chisq	**p-value**	**Gfi**	**cfi**	**Srmr**	**aic**
6.314	0.023	0.992	0.910	0.0400	272.732

Appendix 18 Summary of direct and indirect relationship amongst AGB, SSD, Clay loam, and CNP in single species forests of Pakistan (Figure 31 AB).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.Iv	std.all
AGB	~	SSD	0.005	0.024	0.2	0.841	-0.043	0.052	0.005	0.019
AGB	~	Clay loam	0.033	0.019	1.752	0.08	-0.004	0.069	0.033	0.168
AGB	~	CNP	0.154	0.02	7.552	0.000	0.114	0.194	0.154	0.713
AGB	~	Topography	0.238	0.065	3.666	0.000	0.111	0.365	0.238	0.367
SSD	~	Clay loam	0.153	0.104	1.479	0.139	-0.05	0.357	0.153	0.2
SSD	~	CNP	0.181	0.113	1.604	0.109	-0.04	0.402	0.181	0.213
SSD	~	Topography	0.656	0.356	1.842	0.066	-0.042	1.355	0.656	0.258
Clay loam	~	Topography	1.252	0.439	2.85	0.004	0.391	2.114	1.252	0.378
CNP	~	Topography	-0.817	0.396	-2.064	0.039	-1.593	-0.041	-0.81	-0.273
AGB	~~	AGB	0.011	0.002	5.148	0.000	0.007	0.015	0.011	0.401
SSD	~~	SSD	0.345	0.067	5.148	0.000	0.214	0.476	0.345	0.837
Topography	~~	Topography	0.064	0.000	NA	NA	0.064	0.064	0.064	1.000
AGB	r2	AGB	0.599	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.163	NA	NA	NA	NA	NA	NA	NA
Clay loam	r2	Clay loam	0.139	NA	NA	NA	NA	NA	NA	NA
CNP	r2	CNP	0.074	NA	NA	NA	NA	NA	NA	NA

Appendix 19 Summary relationship of the linear SEM for founding the relationship amongst AGB, SSD, SmP, and SMP in single species forests of Pakistan (Figure 31 B).

Response	Predictor	ß-Value	Std. Err	z-value	P-Value
AGB	SSD	0.052	0.033	1.553	0.121
AGB	SmP	0.012	0.02	0.618	0.536
AGB	SMP	0.049*	0.025	1.983	0.047
AGB	Topography	0.121	0.084	1.438	0.15
SSD	SmP	0.014	0.081	0.171	0.865
SSD	SMP	0.089	0.102	0.872	0.383
SSD	Topography	0.684*	0.334	2.046	0.041
SmP	Topography	0.081	0.568	0.143	0.886
SMP	Topography	-0.117	0.452	-0.258	0.797
Chisq	**pvalue**	**Gfi**	**cfi**	**Srmr**	**aic**
6.214	0.004	0.892	0.710	0.0412	361.102

Appendix 20 Summary of direct and indirect relationship amongst AGB, SSD, SmP, and SMP in single species forests of Pakistan (Figure 31 B).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.lv	std.all
AGB	~	SSD	0.052	0.033	1.553	0.121	-0.014	0.117	0.052	0.202
AGB	~	SmP	0.012	0.02	0.618	0.536	-0.026	0.05	0.012	0.077
AGB	~	SMP	0.049	0.02	1.983	0.047	0.001	0.097	0.049	0.25
AGB	~	Topography	0.121	0.08	1.438	0.15	-0.044	0.285	0.121	0.186
SSD	~	SmP	0.014	0.08	0.171	0.865	-0.145	0.172	0.014	0.022
SSD	~	SMP	0.089	0.10	0.872	0.383	-0.11	0.288	0.089	0.115
SSD	~	Topography	0.684	0.33	2.046	0.041	0.029	1.339	0.684	0.269
SmP	~	Topography	0.081	0.56	0.143	0.886	-1.032	1.195	0.081	0.02
SMP	~	Topography	-0.117	0.45	-0.258	0.797	-1.003	0.77	-0.117	-0.035
AGB	~~	AGB	0.022	0.00	5.148	0.000	0.014	0.03	0.022	0.825
SSD	~~	SSD	0.378	0.07	5.148	0.000	0.234	0.521	0.378	0.916
Topography	~~	Topography	0.064	0.00	NA	NA	0.064	0.064	0.064	1.000
AGB	r2	AGB	0.175	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.084	NA	NA	NA	NA	NA	NA	NA
SmP	r2	SmP	0.004	NA	NA	NA	NA	NA	NA	NA
SMP	r2	SMP	0.001	NA	NA	NA	NA	NA	NA	NA

Appendix 21 Summary relationship of the linear SEM for founding the relationship amongst AGB, SSD, Mt, and MP in single species forests of Pakistan (Figure 32 A).

Response	Predictor	ß-Value	Std. Err	z-value	P-Value
AGB	SSD	0.047	0.029	1.615	0.106
AGB	Mt	-0.331	0.075	-4.427	0
AGB	MP	0.03	0.023	-0.006	0.005
AGB	Topography	0.413	0.1	4.136	0
SSD	Mt	-0.218	0.35	-0.624	0.533
SSD	MP	0.033	0.109	0.303	0.762
SSD	Topography	0.88	0.452	1.947	0.052
Mt	Topography	-0.863	0.132	6.519	0
MP	Topography	-0.37	0.434	-0.853	0.394
Chisq	**Pvalue**	**gfi**	**cfi**	**Srmr**	**aic**
3.215	0.014	0.952	0.810	0.480	188.796

Appendix 22 Summary of direct and indirect relationship amongst AGB, SSD, Mt, and MP in single species forests of Pakistan (Figure 32 A).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.lv	std. all
AGB	~	SSD	0.047	0.029	1.615	0.106	-0.01	0.105	0.047	0.186
AGB	~	Mt	-0.331	0.075	-4.427	0	-0.478	-0.185	-0.331	-0.677
AGB	~	MP	0	0.023	-0.006	0.995	-0.046	0.045	0	-0.001
AGB	~	Topography	0.413	0.1	4.136	0	0.217	0.608	0.413	0.638
SSD	~	Mt	-0.218	0.35	-0.624	0.533	-0.903	0.467	-0.218	-0.114
SSD	~	MP	0.033	0.109	0.303	0.762	-0.18	0.246	0.033	0.041
SSD	~	Topography	0.88	0.452	1.947	0.052	-0.006	1.767	0.88	0.346
Mt	~	Topography	-0.863	0.132	6.519	0	0.604	1.123	0.863	0.652
MP	~	Topography	0.37	0.434	-0.853	0.394	-1.221	0.481	-0.37	-0.116
AGB	~~	AGB	0.017	0.003	5.148	0	0.011	0.024	0.017	0.644
SSD	~~	SSD	0.379	0.074	5.148	0	0.235	0.523	0.379	0.919
Topography	~~	Topography	0.064	0	NA	NA	0.064	0.064	0.064	1
AGB	r2	AGB	0.356	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.081	NA	NA	NA	NA	NA	NA	NA
Mt	r2	Mt	0.477	NA	NA	NA	NA	NA	NA	NA
MP	r2	MP	0.014	NA	NA	NA	NA	NA	NA	NA

Appendix 2123 Summary relationship of the linear SEM for founding the relationship amongst AGB, SSD, MRH, and MWP in single species forests of Pakistan (Figure 32 B).

Response	**Predictor**	**ß-Value**	**Std.Err**	**z-value**	**P-Value**
AGB	SSD	0.049	0.027	1.816	0.069
AGB	MRH	1.107	1.477	0.749	0.454
AGB	MWP	1.277	1.964	0.65	0.516
AGB	Topoghraphy	0.312	0.078	4.03	0
SSD	MRH	-1.263	7.478	-0.169	0.866
SSD	MWP	-1.773	9.941	-0.178	0.858
SSD	Topoghraphy	0.758	0.378	2.002	0.045
MRH	Topoghraphy	-0.006	0.007	-0.923	0.356
MWP	Topoghraphy	0.966	0.264	3.66	0
chisq	**pvalue**	**gfi**	**cfi**	**srmr**	**aic**
0.000	0.000	1.000	1.000	0.000	196.007

Appendix 2134 Summary of direct and indirect relationship amongst AGB, SSD, MRH, and MWP in single species forests of Pakistan. (Figure 32 B).

Response	**OP**	**Predictor**	**ß-Value**	**SE**	**Z-Value**	**P-value**	**Ci.lower**	**Ci.upper**	**std.Iv**	**std.all**
AGB	~	SSD	0.049	0.02	1.816	0.069	-0.004	0.102	0.049	0.193
AGB	~	MRH	1.107	1.47	0.749	0.454	-1.788	4.002	1.107	4.894
AGB	~	MWP	1.277	1.96	0.65	0.516	-2.572	5.126	1.277	4.242
AGB	~	Topoghraphy	0.312	0.07	4.03	0	0.16	0.464	0.312	0.483
SSD	~	MRH	-1.26	7.47	-0.16	0.866	-15.92	13.394	-1.26	-1.422
SSD	~	MWP	-1.73	9.94	-0.17	0.858	-21.258	17.712	-1.77	-1.5
SSD	~	Topoghraphy	0.758	0.37	2.002	0.045	0.016	1.5	0.758	0.298
MRH	~	MWP	-1.32	0.00	-414.	0	-1.335	-1.323	-1.32	-0.99
MRH	~	Topoghraphy	-0.06	0.00	-0.92	0.356	-0.02	0.007	-0.00	-0.00
MWP	~	Topoghraphy	0.966	0.26	3.66	0	0.448	1.483	0.966	0.449
AGB	~~	AGB	0.015	0.00	5.148	0	0.009	0.021	0.015	0.556
SSD	~~	SSD	0.381	0.07	5.148	0	0.236	0.526	0.381	0.924
MRH	~~	MRH	0	0	5.148	0	0	0	0	0
MWP	~~	MWP	0.236	0.04	5.148	0	0.146	0.325	0.236	0.798
Topoghraphy	~~	Topoghraphy	0.064	0	NA	NA	0.064	0.064	0.064	1
AGB	r2	AGB	0.444	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.076	NA	NA	NA	NA	NA	NA	NA
MRH	r2	MRH	1	NA	NA	NA	NA	NA	NA	NA
MWP	r2	MWP	0.202	NA	NA	NA	NA	NA	NA	NA

Appendix 2145 Summary relationship of the linear SEM for founding the relationship amongst AGB, SSD, Clay loam, and CNP in multi-species forests of Pakistan (Figure 33 A).

Response	Predictor	ß-Value	Std. Err	z-value	P-Value
AGB	SSD	0.081*	0.031	2.583	0.01
AGB	Clay loam	0.023	0.018	1.282	0.2
AGB	CNP	0.098***	0.027	3.583	0.000
AGB	Topography	0.016	0.028	0.561	0.575
SSD	Clay loam	-0.047	0.048	-0.984	0.325
SSD	CNP	-0.016	0.072	-0.222	0.824
SSD	Topography	0.343***	0.069	4.959	0.000
Clay loam	Topography	0.164	0.118	1.381	0.167
CNP	Topography	0.776***	0.048	16.314	0.000
Chisq	**pvalue**	**Gfi**	**Cfi**	**Srmr**	**aic**
6.332	0.034	0.929	0.8299	0.423	851.558

Appendix 26 Summary of direct and indirect relationship amongst AGB, SSD, Clay loam, and CNP in multi-species forests of Pakistan (Figure 33 A).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.lv	std. all
AGB	~	SSD	0.081	0.031	2.583	0.01	0.019	0.142	0.081	0.2
AGB	~	Clay loam	0.023	0.018	1.282	0.2	-0.012	0.059	0.023	0.093
AGB	~	CNP	0.098	0.027	3.583	0	0.044	0.152	0.098	0.398
AGB	~	Topography	0.016	0.028	0.561	0.575	-0.04	0.071	0.016	0.067
SSD	~	Clay loam	-0.047	0.048	-0.984	0.325	-0.141	0.047	-0.04	-0.076
SSD	~	CNP	-0.016	0.072	-0.222	0.824	-0.157	0.125	-0.01	-0.026
SSD	~	Topography	0.343	0.069	4.959	0	0.207	0.478	0.343	0.582
Clay loam	~	CNP	0.264	0.122	2.153	0.031	0.024	0.503	0.264	0.27
Clay loam	~	Topography	0.164	0.118	1.381	0.167	-0.068	0.396	0.164	0.173
CNP	~	Topography	0.776	0.048	16.314	0	0.683	0.87	0.776	0.803
AGB	~~	AGB	0.039	0.005	8.573	0	0.03	0.048	0.039	0.626
SSD	~~	SSD	0.273	0.032	8.573	0	0.21	0.335	0.273	0.712
Clay loam	~~	Clay loam	0.81	0.094	8.573	0	0.625	0.995	0.81	0.822
CNP	~~	CNP	0.368	0.043	8.573	0	0.284	0.452	0.368	0.356

Topography	~~	Topography	1.105	0	NA	NA	1.105	1.105	1.105	1
AGB	r2	AGB	0.374	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.288	NA	NA	NA	NA	NA	NA	NA
Clay loam	r2	Clay loam	0.178	NA	NA	NA	NA	NA	NA	NA
CNP	r2	CNP	0.644	NA	NA	NA	NA	NA	NA	NA

Appendix 27 Summary relationship of the linear SEM for founding the relationship amongst AGB, SSD, SmP, and SMP in multi-species forests of Pakistan (Figure 33 B).

Response	**Predictor**	**ß-Value**	**Std. Err**	**z-value**	**P-Value**
AGB	SSD	0.063*	0.032	1.988	0.047
AGB	SmP	0.032	0.017	1.845	0.065
AGB	SMP	0.056**	0.019	2.994	0.003
AGB	Topography	0.085***	0.02	4.202	0.000
SSD	SmP	0.052	0.045	1.156	0.248
SSD	SMP	0.037	0.048	0.758	0.449
SSD	Topography	0.303***	0.046	6.567	0.000
SmP	SMP	-0.113	0.089	-1.274	0.203
SmP	Topography	-0.073	0.085	-0.856	0.392
SMP	Topography	0.443***	0.07	6.291	0.000
Chisq	**p-value**	**Gfi**	**Cfi**	**srmr**	**aic**
3.321	0.021	0.994	0.880	0.910	991.272

Appendix 28 Summary of direct and indirect relationship amongst AGB, SSD, SmP, and SMP in multi-species forests of Pakistan (Figure 33 B).

Response	**OP**	**Predictor**	**ß-Value**	**SE**	**Z-Value**	**P-value**	**Ci.lower**	**Ci.upper**	**std.lv**	**std.all**
AGB	~	SSD	0.063	0.032	1.988	0.047	0.001	0.126	0.063	0.157
AGB	~	SmP	0.032	0.017	1.845	0.065	-0.002	0.066	0.032	0.125
AGB	~	SMP	0.056	0.019	2.994	0.003	0.019	0.092	0.056	0.225
AGB	~	Topoghraphy	0.085	0.02	4.202	0	0.045	0.125	0.085	0.358
SSD	~	SmP	0.052	0.045	1.156	0.248	-0.036	0.139	0.052	0.081
SSD	~	SMP	0.037	0.048	0.758	0.449	-0.058	0.131	0.037	0.06
SSD	~	Topoghraphy	0.303	0.046	6.567	0	0.213	0.394	0.303	0.515
SmP	~	SMP	-0.113	0.089	-1.274	0.203	-0.287	0.061	-0.113	-0.117
SmP	~	Topoghraphy	-0.073	0.085	-0.856	0.392	-0.24	0.094	-0.073	-0.078

SMP	~	Topoghraphy	0.443	0.07	6.291	0	0.305	0.581	0.443	0.461
AGB	~~	AGB	0.041	0.005	8.573	0	0.031	0.05	0.041	0.647
SSD	~~	SSD	0.272	0.032	8.573	0	0.21	0.334	0.272	0.709
SmP	~~	SmP	0.93	0.108	8.573	0	0.717	1.142	0.93	0.972
SMP	~~	SMP	0.805	0.094	8.573	0	0.621	0.989	0.805	0.788
Topoghraphy	~~	Topoghraphy	1.105	0	NA	NA	1.105	1.105	1.105	1
AGB	r2	AGB	0.353	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.291	NA	NA	NA	NA	NA	NA	NA
SmP	r2	SmP	0.028	NA	NA	NA	NA	NA	NA	NA
SMP	r2	SMP	0.212	NA	NA	NA	NA	NA	NA	NA

Appendix 29 Summary relationship of the linear SEM for founding the relationship amongst AGB, SSD, Mt, and MP in single species forests of Pakistan (Figure 34 A).

Response	**Predictor**	**ß-Value**	**Std.Err**	**z-value**	**P-Value**
AGB	SSD	0.124***	0.032	3.822	0.000
AGB	Mt	0.151***	0.033	4.572	0.000
AGB	MP	0.027	0.026	1.017	0.309
AGB	Topography	0.212***	0.03	7.097	0.000
SSD	Mt	-0.31	0.08	-3.855	0.000
SSD	MP	-0.035	0.067	-0.528	0.597
SSD	Topography	0.046	0.076	0.609	0.543
Mt	MP	-0.41	0.059	-6.896	0.000
Mt	Topography	-0.679	0.054	-12.496	0.000
MP	Topography	0.619***	0.055	11.165	0.000
Chisq	**Pvalue**	**Gfi**	**cfi**	**Srmr**	**aic**
0.000	0.000	1.000	1.000	0.000	708.554

Appendix 30 Summary of direct and indirect relationship amongst AGB, SSD, Mt, and MP in multi-species forests of Pakistan (Figure 34 A).

Response	**OP**	**Predictor**	**ß-Value**	**SE**	**Z-Value**	**P-value**	**Ci.lower**	**Ci.upper**	**std.lv**	**std.all**
AGB	~	SSD	0.124	0.032	3.822	0	0.06	0.187	0.124	0.306
AGB	~	Mt	0.151	0.033	4.572	0	0.086	0.216	0.151	0.689
AGB	~	MP	0.027	0.026	1.017	0.309	-0.025	0.078	0.027	0.102
AGB	~	Topoghraphy	0.212	0.03	7.097	0	0.153	0.27	0.212	0.889
SSD	~	Mt	-0.31	0.08	-3.855	0	-0.467	-0.152	-0.31	-0.571
SSD	~	MP	-0.035	0.067	-0.528	0.597	-0.166	0.095	-0.035	-0.055
SSD	~	Topoghraphy	0.046	0.076	0.609	0.543	-0.103	0.195	0.046	0.078
Mt	~	MP	-0.41	0.059	-6.896	0	-0.526	-0.293	-0.41	-0.345
Mt	~	Topoghraphy	-0.679	0.054	-12.496	0	-0.785	-0.572	-0.679	-0.625

MP	~	Topoghraphy	0.619	0.055	11.165	0	0.511	0.728	0.619	0.677
AGB	~~	AGB	0.038	0.004	8.573	0	0.029	0.046	0.038	0.603
SSD	~~	SSD	0.246	0.029	8.573	0	0.19	0.302	0.246	0.641
Mt	~~	Mt	0.259	0.03	8.573	0	0.2	0.319	0.259	0.199
MP	~~	MP	0.5	0.058	8.573	0	0.386	0.614	0.5	0.541
Topoghraphy	~~	Topoghraphy	1.105	0	NA	NA	1.105	1.105	1.105	1
AGB	r2	AGB	0.397	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.359	NA	NA	NA	NA	NA	NA	NA
Mt	r2	Mt	0.801	NA	NA	NA	NA	NA	NA	NA
MP	r2	MP	0.459	NA	NA	NA	NA	NA	NA	NA

Appendix 3151 Summary relationship of the linear SEM for founding the relationship amongst AGB, SSD, MRH, and MWP in multi-species forests of Pakistan (Figure 34 B).

Response	**Predictor**	**ß-Value**	**Std. Err**	**z-value**	**P-Value**
AGB	SSD	0.135***	0.032	4.163	0.000
AGB	MRH	-0.191	0.037	-5.159	0.000
AGB	MWP	-0.066	0.025	-2.595	0.009
AGB	Topography	0.128***	0.023	5.668	0.000
SSD	MRH	0.409***	0.088	4.636	0.000
SSD	MWP	0.141*	0.063	2.222	0.026
SSD	Topography	0.22	0.054	4.037	0.000
MRH	MWP	-0.441	0.047	-9.433	0.000
MRH	Topography	0.159**	0.049	3.238	0.001
MWP	Topography	-0.719	0.063	-11.362	0.000
Chisq	**Pvalue**	**Gfi**	**Cfi**	**srmr**	**aic**
3.321	0.021	0.994	0.880	0.910	706.9

Appendix 32 Summary of direct and indirect relationship amongst AGB, SSD, MRH, and MWP in single species forests of Pakistan (Figure 34 B).

Response	**OP**	**Predictor**	**ß-Value**	**SE**	**Z-Value**	**P-value**	**Ci.lower**	**Ci.upper**	**std.lv**	**std.all**
AGB	~	SSD	0.135	0.032	4.163	0	0.071	0.198	0.135	0.333
AGB	~	MRH	-0.191	0.037	-5.159	0	-0.264	-0.119	-0.19	-0.585
AGB	~	MWP	-0.066	0.025	-2.595	0.009	-0.115	-0.016	-0.06	-0.29
AGB	~	Topoghraphy	0.128	0.023	5.668	0	0.083	0.172	0.128	0.536
SSD	~	MRH	0.409	0.088	4.636	0	0.236	0.583	0.409	0.506
SSD	~	MWP	0.141	0.063	2.222	0.026	0.017	0.265	0.141	0.251

SSD	~	Topoghraphy	0.22	0.054	4.037	0	0.113	0.326	0.22	0.373
MRH	~	MWP	-0.441	0.047	-9.433	0	-0.532	-0.349	-0.44	-0.637
MRH	~	Topoghraphy	0.159	0.049	3.238	0.001	0.063	0.255	0.159	0.219
MWP	~	Topoghraphy	-0.719	0.063	-11.36	0	-0.843	-0.595	-0.71	-0.684
AGB	~~	AGB	0.037	0.004	8.573	0	0.028	0.045	0.037	0.588
SSD	~~	SSD	0.239	0.028	8.573	0	0.184	0.294	0.239	0.623
MRH	~~	MRH	0.208	0.024	8.573	0	0.161	0.256	0.208	0.357
MWP	~~	MWP	0.65	0.076	8.573	0	0.501	0.798	0.65	0.532
Topoghraphy	~~	Topoghraphy	1.105	0	NA	NA	1.105	1.105	1.105	1
AGB	r2	AGB	0.412	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.377	NA	NA	NA	NA	NA	NA	NA
MRH	r2	MRH	0.643	NA	NA	NA	NA	NA	NA	NA
MWP	r2	MWP	0.468	NA	NA	NA	NA	NA	NA	NA

Appendix 33 Summary relationship of the linear SEM for founding the relationship amongst AGB, CWM, BT, SSD, clay loam, and CNP in the natural forest ecosystem of Pakistan (Figure 42 A).

Response	**Predictor**	**ß-Value**	**Std. Err**	**z-value**	**P-Value**
AGB	CWM	0.023	0.073	0.319	0.75
AGB	SR	-0.015	0.073	-0.21	0.834
AGB	BTSSD	0.184	0.089	2.058	0.04
AGB	Clay loam	0.027	0.076	0.349	0.727
AGB	CNP	0.1	0.089	1.125	0.261
CWM	SR	0.197	0.069	2.859	0.004
CWM	BTSSD	-0.204	0.085	-2.397	0.017
CWM	Clay loam	0.108	0.073	1.477	0.14
CWM	CNP	0.272	0.084	3.253	0.001
SR	BTSSD	-0.344	0.084	-4.111	0.000
SR	Clay loam	0.095	0.075	1.27	0.204
SR	CNP	0.292	0.083	3.502	0.000
BTSSD	Clay loam	0.206	0.062	3.352	0.001
BTSSD	CNP	0.483	0.062	7.85	0.000
Clay loam	CNP	0.383	0.065	5.865	0.000
Chisq	**p-value**	**Gfi**	**cfi**	**srmr**	**aic**
3.431	0.025	0.982	0.891	0.911	2689.182

Appendix 34 Summary of direct and indirect relationship amongst AGB, CWM, BTSSD, clay loam, and CNP in natural forests of Pakistan (Figure 42 A).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.lv	std. all
AGB	~	CWM	0.023	0.073	0.319	0.75	-0.12	0.167	0.023	0.023
AGB	~	SR	-0.015	0.073	-0.21	0.834	-0.158	0.128	-0.01	-0.01
AGB	~	BTSSD	0.184	0.089	2.058	0.04	0.009	0.359	0.184	0.184
AGB	~	Clay loam	0.027	0.076	0.349	0.727	-0.123	0.177	0.027	0.027
AGB	~	CNP	0.1	0.089	1.125	0.261	-0.074	0.275	0.1	0.1
CWM	~	SR	0.197	0.069	2.859	0.004	0.062	0.333	0.197	0.197
CWM	~	BTSSD	-0.204	0.085	-2.397	0.017	-0.37	-0.037	-0.20	-0.204
CWM	~	Clay loam	0.108	0.073	1.477	0.14	-0.035	0.252	0.108	0.108
CWM	~	CNP	0.272	0.084	3.253	0.001	0.108	0.437	0.272	0.272
SR	~	BTSSD	-0.344	0.084	-4.111	0.000	-0.508	-0.18	-0.34	-0.344
SR	~	Clay loam	0.095	0.075	1.27	0.204	-0.052	0.242	0.095	0.095
SR	~	CNP	0.292	0.083	3.502	0.999	0.128	0.455	0.292	0.292
BTSSD	~	Clay loam	0.206	0.062	3.352	0.001	0.086	0.327	0.206	0.206
BTSSD	~	CNP	0.483	0.062	7.85	0.000	0.363	0.604	0.483	0.483
Clay loam	~	CNP	0.383	0.065	5.865	0.000	0.255	0.511	0.383	0.383
AGB	~~	AGB	0.922	0.092	10	0.000	0.742	1.103	0.922	0.927
CWM	~~	CWM	0.857	0.086	10	0.000	0.689	1.025	0.857	0.862
SR	~~	SR	0.9	0.09	10	0.000	0.724	1.077	0.9	0.905
BTSSD	~~	BTSSD	0.644	0.064	10	0.000	0.518	0.77	0.644	0.647
Clay loam	~~	Clay loam	0.849	0.085	10	0.000	0.683	1.015	0.849	0.853
CNP	~~	CNP	0.995	0.000	NA	NA	0.995	0.995	0.995	1.000
AGB	r2	AGB	0.073	NA	NA	NA	NA	NA	NA	NA
CWM	r2	CWM	0.138	NA	NA	NA	NA	NA	NA	NA
SR	r2	SR	0.095	NA	NA	NA	NA	NA	NA	NA
BTSSD	r2	BTSSD	0.353	NA	NA	NA	NA	NA	NA	NA
Clay loam	r2	Clay loam	0.147	NA	NA	NA	NA	NA	NA	NA

Appendix 35 Summary relationship of the linear SEM for founding the relationship amongst AGB, BTSSD, SmP, and SMP in the natural forests of Pakistan (Figure 42 B).

Response	Predictor	ß-Value	Std. Err	z-value	P-Value
AGB ~	CWM	0.028	0.072	0.384	0.701
AGB ~	SR	0.019	0.072	0.262	0.794
AGB ~	BTSSD	0.23	0.074	3.118	0.002
AGB ~	SmP	0.105	0.07	1.493	0.136
AGB ~	SMP	-0.037	0.073	-0.512	0.609
CWM ~	SR	0.285	0.068	4.17	0.000
CWM ~	BTSSD	-0.044	0.073	-0.61	0.542
CWM ~	SmP	0.161	0.068	2.361	0.018
CWM ~	SMP	-0.083	0.071	-1.161	0.245
SR ~	BTSSD	-0.15	0.074	-2.02	0.043
SR ~	SmP	-0.114	0.07	-1.633	0.103
SR ~	SMP	-0.067	0.074	-0.908	0.364
BTSSD ~	SmP	0.132	0.066	2.005	0.045
BTSSD ~	SMP	-0.338	0.066	-5.134	0.000
SmP ~	SMP	0.01	0.071	0.138	0.89
chisq	**p-value**	**Gfi**	**cfi**	**srmr**	**Aic**
3.541	0.029	0.97	0.902	0.912	2799.169

Appendix 36 Summary of direct and indirect relationship amongst AGB, BTSSD, SmP, and SMP in the natural forests of Pakistan (Figure 42 B).

Response	**OP**	**Predictor**	**ß-Value**	**SE**	**Z-Value**	**P-value**	**Ci.lower**	**Ci.upper**	**std.Iv**	**std. all**
AGB	~	CWM	0.028	0.072	0.384	0.701	-0.113	0.168	0.028	0.028
AGB	~	SR	0.019	0.072	0.262	0.794	-0.123	0.16	0.019	0.019
AGB	~	BTSSD	0.23	0.074	3.118	0.002	0.085	0.374	0.23	0.23
AGB	~	SmP	0.105	0.07	1.493	0.136	-0.033	0.242	0.105	0.105
AGB	~	SMP	-0.03	0.073	-0.51	0.609	-0.18	0.105	-0.03	-0.037
CWM	~	SR	0.285	0.068	4.17	0	0.151	0.418	0.285	0.285
CWM	~	BTSSD	-0.04	0.073	-0.61	0.542	-0.186	0.098	-0.04	-0.044
CWM	~	SmP	0.161	0.068	2.361	0.018	0.027	0.294	0.161	0.161
CWM	~	SMP	-0.08	0.071	-1.16	0.245	-0.223	0.057	-0.08	-0.083
SR	~	BTSSD	-0.15	0.074	-2.02	0.043	-0.296	-0.004	-0.15	-0.15
SR	~	SmP	-0.11	0.07	-1.63	0.103	-0.252	0.023	-0.11	-0.114
SR	~	SMP	-0.06	0.074	-0.90	0.364	-0.212	0.078	-0.0	-0.067
BTSSD	~	SmP	0.132	0.066	2.005	0.045	0.003	0.261	0.132	0.132
BTSSD	~	SMP	-0.33	0.066	-5.13	0.000	-0.468	-0.209	-0.33	-0.338
SmP	~	SMP	0.01	0.071	0.138	0.89	-0.129	0.148	0.01	0.01
AGB	~~	AGB	0.918	0.092	10	0.000	0.738	1.098	0.918	0.923
CWM	~~	CWM	0.892	0.089	10	0.000	0.717	1.067	0.892	0.897
SR	~~	SR	0.957	0.096	10	0.000	0.77	1.145	0.957	0.962
BTSSD	~~	BTSSD	0.865	0.086	10	0.000	0.695	1.034	0.865	0.869
SmP	~~	SmP	0.995	0.099	10	0.000	0.8	1.19	0.995	1.000
SMP	~~	SMP	0.995	0.000	NA	NA	0.995	0.995	0.995	1.000
AGB	r2	AGB	0.077	NA	NA	NA	NA	NA	NA	NA
CWM	r2	CWM	0.103	NA	NA	NA	NA	NA	NA	NA
SR	r2	SR	0.038	NA	NA	NA	NA	NA	NA	NA
BTSSD	r2	BTSSD	0.131	NA	NA	NA	NA	NA	NA	NA
SmP	r2	SmP	0	NA	NA	NA	NA	NA	NA	NA

Appendix 37 Summary relationship of the linear SEM for founding the relationship amongst AGB, SD, CWM, Mt, and MP in the natrual forests of Pakistan (Figure 43 A).

Response	**Predictor**	**ß-Value**	**Std. Err**	**z-value**	**P-Value**
AGB ~	SD	-0.015	0.018	-0.84	0.401
AGB ~	CWM	0.018	0.018	1.006	0.314
AGB ~	BT	0.177	0.016	11.247	0
AGB ~	Mt	0.008	0.02	0.389	0.697
AGB ~	MP	0.015	0.02	0.741	0.459
SD ~	CWM	0.463	0.061	7.636	0
SD ~	BT	-0.24	0.059	-4.06	0
SD ~	Mt	0.053	0.08	0.665	0.506
SD ~	MP	0.305	0.075	4.052	0
CWM ~	BT	-0.127	0.069	-1.86	0.063
CWM ~	Mt	-0.325	0.09	-3.595	0
CWM ~	MP	0.159	0.087	1.822	0.068
BT ~	Mt	-0.349	0.09	-3.869	0
BT ~	MP	-0.001	0.09	-0.013	0.989
Mt ~	MP	-0.678	0.052	-12.972	0
Chisq	**pvalue**	**gfi**	**cfi**	**srmr**	**Aic**
3.651	0.033	0.958	0.913	0.913	1930.605

Appendix 38 Summary of direct and indirect relationship amongst AGB, SSD, MRH, and MWP in single species forests of Pakistan (Figure 43 A).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.Iv	std. all
AGB	~	SD	-0.015	0.018	-0.84	0.401	-0.051	0.02	-0.015	-0.056
AGB	~	CWM	0.018	0.018	1.006	0.314	-0.017	0.052	0.018	0.066
AGB	~	BT	0.177	0.016	11.247	0.000	0.146	0.208	0.177	0.658
AGB	~	Mt	0.008	0.02	0.389	0.697	-0.032	0.048	0.008	0.03
AGB	~	MP	0.015	0.02	0.741	0.459	-0.024	0.054	0.015	0.055
SD	~	CWM	0.463	0.061	7.636	0.000	0.344	0.582	0.463	0.464
SD	~	BT	-0.24	0.059	-4.06	0.000	-0.356	-0.124	-0.24	-0.241
SD	~	Mt	0.053	0.08	0.665	0.506	-0.103	0.21	0.053	0.053
SD	~	MP	0.305	0.075	4.052	0.000	0.158	0.453	0.305	0.306
CWM	~	BT	-0.127	0.069	-1.86	0.063	-0.262	0.007	-0.127	-0.127
CWM	~	Mt	-0.325	0.09	-3.595	0.000	-0.502	-0.148	-0.325	-0.325
CWM	~	MP	0.159	0.087	1.822	0.068	-0.012	0.33	0.159	0.159
BT	~	Mt	-0.349	0.09	-3.869	0.000	-0.526	-0.172	-0.349	-0.349
BT	~	MP	-0.001	0.09	-0.013	0.989	-0.178	0.176	-0.001	-0.001
Mt	~	MP	-0.678	0.052	-12.97	0.000	-0.78	-0.575	-0.678	-0.677
AGB	~~	AGB	0.039	0.004	9.975	0.000	0.032	0.047	0.039	0.543
SD	~~	SD	0.6	0.06	9.975	0.000	0.482	0.718	0.6	0.604
CWM	~~	CWM	0.819	0.082	9.975	0.000	0.658	0.98	0.819	0.821
BT	~~	BT	0.876	0.088	9.975	0.000	0.704	1.049	0.876	0.879
Mt	~~	Mt	0.542	0.054	9.975	0.000	0.435	0.648	0.542	0.542
MP	~~	MP	0.998	0.000	NA	NAB	0.998	0.998	0.998	1.000
AGB	r2	AGB	0.457	NA	NA	NA	NA	NA	NA	NA
SD	r2	SD	0.396	NA	NA	NA	NA	NA	NA	NA
CWM	r2	CWM	0.179	NA	NA	NA	NA	NA	NA	NA
BT	r2	BT	0.121	NA	NA	NA	NA	NA	NA	NA
Mt	r2	Mt	0.458	NA	NA	NA	NA	NA	NA	NA

Appendix 39 Summary relationship of the linear SEM for founding the relationship amongst AGB, BT, SD, MRH, and MWP in the natrual forests of Pakistan (Figure 43 B).

Response	**Predictor**	**ß-Value**	**Std. Err**	**z-value**	**P-Value**
AGB ~	SD	-0.018	0.02	-0.927	0.354
AGB ~	CWM	0.017	0.019	0.902	0.367
AGB ~	BT	0.172	0.016	10.669	0.000
AGB ~	MRH	-0.008	0.023	-0.337	0.736
AGB ~	MWP	-0.024	0.02	-1.167	0.243
SD ~	CWM	0.254	0.064	3.966	0.000
SD ~	BT	-0.317	0.053	-5.947	0.000
SD ~	MRH	0.35	0.08	4.362	0.000
SD ~	MWP	-0.21	0.071	-2.94	0.003
CWM ~	BT	-0.109	0.059	-1.865	0.062
CWM ~	MRH	0.619	0.077	8.009	0.000
CWM ~	MWP	-0.018	0.079	-0.234	0.815
BT ~	MRH	-0.002	0.094	-0.021	0.983
BT ~	MWP	-0.302	0.093	-3.234	0.001
MRH ~	MWP	-0.686	0.051	-13.404	0.000
Chisq	**pvalue**	**Gfi**	**Cfi**	**srmr**	**Aic**
3.761	0.037	0.946	0.924	0.914	2799.169

Appendix 40 Summary of direct and indirect relationship amongst AGB, SD, CWM, MRH, and MWP in the natural forests of Pakistan (Figure 43 B).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.lv	std. all
AGB	~	SD	-0.018	0.02	-0.927	0.354	-0.057	0.02	-0.018	-0.068
AGB	~	CWM	0.017	0.019	0.902	0.367	-0.02	0.053	0.017	0.062
AGB	~	BT	0.172	0.016	10.669	0	0.14	0.204	0.172	0.638
AGB	~	MRH	-0.008	0.023	-0.337	0.736	-0.054	0.038	-0.008	-0.029
AGB	~	MWP	-0.024	0.02	-1.167	0.243	-0.064	0.016	-0.024	-0.088
SD	~	CWM	0.254	0.064	3.966	0	0.128	0.379	0.254	0.254
SD	~	BT	-0.317	0.053	-5.947	0	-0.421	-0.212	-0.317	-0.317
SD	~	MRH	0.35	0.08	4.362	0	0.193	0.507	0.35	0.349
SD	~	MWP	-0.21	0.071	-2.94	0.003	-0.349	-0.07	-0.21	-0.21
CWM	~	BT	-0.109	0.059	-1.865	0.062	-0.224	0.006	-0.109	-0.109
CWM	~	MRH	0.619	0.077	8.009	0	0.468	0.771	0.619	0.617
CWM	~	MWP	-0.018	0.079	-0.234	0.815	-0.173	0.136	-0.018	-0.018
BT	~	MRH	-0.002	0.094	-0.021	0.983	-0.185	0.182	-0.002	-0.002
BT	~	MWP	-0.302	0.093	-3.234	0.001	-0.484	-0.119	-0.302	-0.302
MRH	~	MWP	-0.686	0.051	-13.40	0	-0.786	-0.586	-0.686	-0.689
AGB	~~	AGB	0.039	0.004	9.975	0	0.031	0.047	0.039	0.541
SD	~~	SD	0.504	0.05	9.975	0	0.405	0.603	0.504	0.506
CWM	~~	CWM	0.619	0.062	9.975	0	0.497	0.741	0.619	0.62
BT	~~	BT	0.908	0.091	9.975	0	0.729	1.086	0.908	0.91
MRH	~~	MRH	0.52	0.052	9.975	0	0.418	0.622	0.52	0.526
MWP	~~	MWP	0.998	0	NA	NA	0.998	0.998	0.998	1
AGB	r2	AGB	0.459	NA	NA	NA	NA	NA	NA	NA
SD	r2	SD	0.494	NA	NA	NA	NA	NA	NA	NA
CWM	r2	CWM	0.38	NA	NA	NA	NA	NA	NA	NA
BT	r2	BT	0.09	NA	NA	NA	NA	NA	NA	NA
MRH	r2	MRH	0.474	NA	NA	NA	NA	NA	NA	NA

Appendix 41 Summary relationship of the linear SEM for founding the relationship amongst AGB, CWM, SR, BTSSD, MTSSD, STSSD, Clay loam, and CNP in the natrual forests of Pakistan (Figure 44 A).

Response	**Predictor**	**ß-Value**	**Std. Err**	**z-value**	**P-Value**
AGB ~	CWM	-0.068	0.067	-1.018	0.309
AGB ~	SR	-0.026	0.062	-0.411	0.681
AGB ~	BTSSD	0.33	0.079	4.175	0.000
AGB ~	MTSSD	0.553	0.061	9.002	0.000
AGB ~	STSSD	0.102	0.069	1.47	0.142
AGB ~	Clay loam	0.029	0.065	0.446	0.656
AGB ~	CNP	-0.026	0.077	-0.335	0.738
CWM ~	SR	0.12	0.065	1.843	0.065
CWM ~	BTSSD	-0.044	0.084	-0.52	0.603
CWM ~	MTSSD	0.165	0.064	2.576	0.01
CWM ~	STSSD	0.381	0.068	5.597	0.000
CWM ~	Clay loam	0.077	0.068	1.124	0.261
CWM ~	CNP	0.257	0.08	3.229	0.001
SR ~	BTSSD	-0.248	0.089	-2.786	0.005
SR ~	MTSSD	0.053	0.069	0.767	0.443
SR ~	STSSD	0.216	0.072	2.99	0.003
SR ~	Clay loam	0.073	0.074	0.991	0.322
SR ~	CNP	0.282	0.084	3.362	0.001
BTSSD ~	MTSSD	-0.194	0.053	-3.632	0.000
BTSSD ~	STSSD	-0.281	0.054	-5.225	0.000
BTSSD ~	Clay loam	0.203	0.057	3.585	0.000
BTSSD ~	CNP	0.457	0.058	7.847	0.000
MTSSD ~	STSSD	-0.111	0.071	-1.559	0.119
MTSSD ~	Clay loam	-0.048	0.075	-0.638	0.524
MTSSD ~	CNP	0.151	0.077	1.965	0.049
STSSD ~	Clay loam	0.023	0.075	0.311	0.755
STSSD ~	CNP	-0.213	0.075	-2.84	0.005
Clay loam ~	CNP	0.383	0.065	5.865	0.000
Chisq	**pvalue**	**Gfi**	**cfi**	**srmr**	**aic**
3.871	0.041	0.934	0.935	0.915	2799.169

Appendix 42 Summary of direct and indirect relationship amongst AGB, CWM, SR, BTSSD, MTSSD, STSSD, Clay loam, and CNP in the natural forests of Pakistan (Figure 44 A).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.Iv	std. all
AGB	~	CWM	-0.068	0.067	-1.018	0.309	-0.199	0.063	-0.068	-0.068
AGB	~	SR	-0.026	0.062	-0.411	0.681	-0.147	0.096	-0.026	-0.026
AGB	~	BTSSD	0.33	0.079	4.175	0	0.175	0.486	0.33	0.33
AGB	~	MTSSD	0.553	0.061	9.002	0	0.433	0.674	0.553	0.553
AGB	~	STSSD	0.102	0.069	1.47	0.142	-0.034	0.237	0.102	0.102
AGB	~	Clay loam	0.029	0.065	0.446	0.656	-0.098	0.155	0.029	0.029
AGB	~	CNP	-0.026	0.077	-0.335	0.738	-0.177	0.125	-0.026	-0.026
CWM	~	SR	0.12	0.065	1.843	0.065	-0.008	0.248	0.12	0.12
CWM	~	BTSSD	-0.044	0.084	-0.52	0.603	-0.208	0.121	-0.044	-0.044
CWM	~	MTSSD	0.165	0.064	2.576	0.01	0.039	0.29	0.165	0.165
CWM	~	STSSD	0.381	0.068	5.597	0	0.247	0.514	0.381	0.381
CWM	~	Clay loam	0.077	0.068	1.124	0.261	-0.057	0.21	0.077	0.077
CWM	~	CNP	0.257	0.08	3.229	0.001	0.101	0.413	0.257	0.257
SR	~	BTSSD	-0.248	0.089	-2.786	0.005	-0.422	-0.073	-0.248	-0.248
SR	~	MTSSD	0.053	0.069	0.767	0.443	-0.083	0.189	0.053	0.053
SR	~	STSSD	0.216	0.072	2.99	0.003	0.074	0.357	0.216	0.216
SR	~	Clay loam	0.073	0.074	0.991	0.322	-0.071	0.217	0.073	0.073
SR	~	CNP	0.282	0.084	3.362	0.001	0.118	0.446	0.282	0.282
BTSSD	~	MTSSD	-0.194	0.053	-3.632	0	-0.298	-0.089	-0.194	-0.194
BTSSD	~	STSSD	-0.281	0.054	-5.225	0	-0.386	-0.175	-0.281	-0.281
BTSSD	~	Clay loam	0.203	0.057	3.585	0	0.092	0.314	0.203	0.203
BTSSD	~	CNP	0.457	0.058	7.847	0	0.343	0.572	0.457	0.457
MTSSD	~	STSSD	-0.111	0.071	-1.559	0.119	-0.249	0.028	-0.111	-0.111
MTSSD	~	Clay loam	-0.048	0.075	-0.638	0.524	-0.195	0.099	-0.048	-0.048
MTSSD	~	CNP	0.151	0.077	1.965	0.049	0	0.301	0.151	0.151
STSSD	~	Clay loam	0.023	0.075	0.311	0.755	-0.124	0.17	0.023	0.023
STSSD	~	CNP	-0.213	0.075	-2.84	0.005	-0.36	-0.066	-0.213	-0.213
Clay loam	~	CNP	0.383	0.065	5.865	0	0.255	0.511	0.383	0.383
AGB	~~	AGB	0.655	0.066	10	0	0.527	0.783	0.655	0.658
CWM	~~	CWM	0.734	0.073	10	0	0.59	0.878	0.734	0.738
SR	~~	SR	0.862	0.086	10	0	0.693	1.031	0.862	0.866
BTSSD	~~	BTSSD	0.544	0.054	10	0	0.437	0.651	0.544	0.547
MTSSD	~~	MTSSD	0.957	0.096	10	0	0.77	1.145	0.957	0.962
STSSD	~~	STSSD	0.953	0.095	10	0	0.766	1.14	0.953	0.958
Clay loam	~~	Clay loam	0.849	0.085	10	0	0.683	1.015	0.849	0.853
CNP	~~	CNP	0.995	0	NA	NA	0.995	0.995	0.995	1
AGB	r2	AGB	0.342	NA	NA	NA	NA	NA	NA	NA
CWM	r2	CWM	0.262	NA	NA	NA	NA	NA	NA	NA
SR	r2	SR	0.134	NA	NA	NA	NA	NA	NA	NA
BTSSD	r2	BTSSD	0.453	NA	NA	NA	NA	NA	NA	NA

MTSSD	r2	MTSSD	0.038	NA	NA	NA	NA	NA	NA	NA
STSSD	r2	STSSD	0.042	NA	NA	NA	NA	NA	NA	NA
Clay loam	r2	Clay loam	0.147	NA	NA	NA	NA	NA	NA	NA

Appendix 43 Summary relationship of the linear SEM for founding the relationship amongst AGB, CWM, SR, BTSSD, MTSSD, STSSD, SmP, and SMP in the natrual forests of Pakistan (Figure 44 B).

Response	**Predictor**	**ß-Value**	**Std. Err**	**z-value**	**P-Value**
AGB ~	CWM	-0.079	0.066	-1.204	0.228
AGB ~	SR	-0.015	0.061	-0.248	0.804
AGB ~	BTSSD	0.332	0.066	5.029	0.000
AGB ~	MTSSD	0.55	0.061	9.044	0.000
AGB ~	STSSD	0.107	0.069	1.55	0.121
AGB ~	SmP	0.066	0.059	1.117	0.264
AGB ~	SMP	0.033	0.062	0.53	0.596
CWM ~	SR	0.195	0.065	3.015	0.003
CWM ~	BTSSD	0.098	0.071	1.387	0.165
CWM ~	MTSSD	0.191	0.064	2.968	0.003
CWM ~	STSSD	0.391	0.069	5.674	0.000
CWM ~	SmP	0.152	0.063	2.409	0.016
CWM ~	SMP	-0.087	0.067	-1.312	0.189
SR ~	BTSSD	-0.057	0.078	-0.732	0.464
SR ~	MTSSD	0.117	0.07	1.675	0.094
SR ~	STSSD	0.233	0.074	3.166	0.002
SR ~	SmP	-0.114	0.069	-1.662	0.097
SR ~	SMP	-0.066	0.073	-0.901	0.368
BTSSD ~	MTSSD	-0.168	0.063	-2.679	0.007
BTSSD ~	STSSD	-0.316	0.063	-4.986	0.000
BTSSD ~	SmP	0.115	0.062	1.863	0.063
BTSSD ~	SMP	-0.299	0.063	-4.743	0.000
MTSSD ~	STSSD	-0.115	0.071	-1.611	0.107
MTSSD ~	SmP	0.067	0.07	0.952	0.341
MTSSD ~	SMP	-0.094	0.071	-1.331	0.183
STSSD ~	SmP	-0.094	0.069	-1.36	0.174
STSSD ~	SMP	0.188	0.069	2.715	0.007
SmP ~	SMP	0.01	0.071	0.138	0.89
Chisq	**Pvalue**	**Gfi**	**cfi**	**srmr**	**aic**
3.981	0.045	0.922	0.946	0.916	3806.43

Appendix 44 Summary of direct and indirect relationship amongst AGB, CWM, SR, BTSSD, MTSSD, STSSD, SmP, and SMP in the natural forests of Pakistan (Figure 44 B).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.lv	std. all
AGB	~	CWM	-0.079	0.066	-1.204	0.228	-0.208	0.05	-0.079	-0.079
AGB	~	SR	-0.015	0.061	-0.248	0.804	-0.135	0.105	-0.015	-0.015
AGB	~	BTSSD	0.332	0.066	5.029	0.000	0.203	0.462	0.332	0.332
AGB	~	MTSSD	0.55	0.061	9.044	0.000	0.431	0.67	0.55	0.55
AGB	~	STSSD	0.107	0.069	1.55	0.121	-0.028	0.242	0.107	0.107
AGB	~	SmP	0.066	0.059	1.117	0.264	-0.05	0.183	0.066	0.066
AGB	~	SMP	0.033	0.062	0.53	0.596	-0.089	0.155	0.033	0.033
CWM	~	SR	0.195	0.065	3.015	0.003	0.068	0.321	0.195	0.195
CWM	~	BTSSD	0.098	0.071	1.387	0.165	-0.041	0.237	0.098	0.098
CWM	~	MTSSD	0.191	0.064	2.968	0.003	0.065	0.316	0.191	0.191
CWM	~	STSSD	0.391	0.069	5.674	0.000	0.256	0.526	0.391	0.391
CWM	~	SmP	0.152	0.063	2.409	0.016	0.028	0.275	0.152	0.152
CWM	~	SMP	-0.087	0.067	-1.312	0.189	-0.218	0.043	-0.087	-0.087
SR	~	BTSSD	-0.057	0.078	-0.732	0.464	-0.209	0.095	-0.057	-0.057
SR	~	MTSSD	0.117	0.07	1.675	0.094	-0.02	0.254	0.117	0.117
SR	~	STSSD	0.233	0.074	3.166	0.002	0.089	0.377	0.233	0.233
SR	~	SmP	-0.114	0.069	-1.662	0.097	-0.248	0.02	-0.114	-0.114
SR	~	SMP	-0.066	0.073	-0.901	0.368	-0.208	0.077	-0.066	-0.066
BTSSD	~	MTSSD	-0.168	0.063	-2.679	0.007	-0.29	-0.045	-0.168	-0.168
BTSSD	~	STSSD	-0.316	0.063	-4.986	0.000	-0.44	-0.192	-0.316	-0.316
BTSSD	~	SmP	0.115	0.062	1.863	0.063	-0.006	0.237	0.115	0.115
BTSSD	~	SMP	-0.299	0.063	-4.743	0.000	-0.422	-0.175	-0.299	-0.299
MTSSD	~	STSSD	-0.115	0.071	-1.611	0.107	-0.254	0.025	-0.115	-0.115
MTSSD	~	SmP	0.067	0.07	0.952	0.341	-0.07	0.204	0.067	0.067
MTSSD	~	SMP	-0.094	0.071	-1.331	0.183	-0.233	0.045	-0.094	-0.094
STSSD	~	SmP	-0.094	0.069	-1.36	0.174	-0.23	0.041	-0.094	-0.094
STSSD	~	SMP	0.188	0.069	2.715	0.007	0.052	0.323	0.188	0.188
SmP	~	SMP	0.01	0.071	0.138	0.89	-0.129	0.148	0.01	0.01
AGB	~~	AGB	0.651	0.065	10	0.000	0.523	0.778	0.651	0.654
CWM	~~	CWM	0.756	0.076	10	0.000	0.608	0.905	0.756	0.76
SR	~~	SR	0.906	0.091	10	0.000	0.728	1.083	0.906	0.91
BTSSD	~~	BTSSD	0.754	0.075	10	0.000	0.606	0.902	0.754	0.758
MTSSD	~~	MTSSD	0.963	0.096	10	0.000	0.775	1.152	0.963	0.968
STSSD	~~	STSSD	0.951	0.095	10	0.000	0.765	1.138	0.951	0.956
SmP	~~	SmP	0.995	0.099	10	0.000	0.8	1.19	0.995	1.000
SMP	~~	SMP	0.995	0.000	NA	NA	0.995	0.995	0.995	1.000
AGB	r2	AGB	0.346	NA	NA	NA	NA	NA	NA	NA
CWM	r2	CWM	0.24	NA	NA	NA	NA	NA	NA	NA
SR	r2	SR	0.09	NA	NA	NA	NA	NA	NA	NA
BTSSD	r2	BTSSD	0.242	NA	NA	NA	NA	NA	NA	NA
MTSSD	r2	MTSSD	0.032	NA	NA	NA	NA	NA	NA	NA
STSSD	r2	STSSD	0.044	NA	NA	NA	NA	NA	NA	NA
SmP	r2	SmP	0.000	NA	NA	NA	NA	NA	NA	NA

Appendix 45 Summary relationship of the linear SEM for founding the relationship amongst AGB, CWM, SR, BTSSD, MTSSD, STSSD, Mt, and MP in the natrual forests of Pakistan (Figure 45 A).

Response	Predictor	ß-Value	Std. Err	z-value	P-Value
AGB ~	SD	-0.012	0.017	-0.726	0.468
AGB ~	CWM	0.01	0.017	0.627	0.531
AGB ~	BT	0.195	0.016	11.888	0.000
AGB ~	MT	0.076	0.014	5.375	0.000
AGB ~	ST	0.009	0.015	0.582	0.56
AGB ~	Mt	0.033	0.02	1.646	0.1
AGB ~	MP	0.021	0.019	1.144	0.252
SD ~	CWM	0.462	0.062	7.507	0.000
SD ~	BT	-0.235	0.066	-3.546	0.000
SD ~	MT	-0.023	0.059	-0.388	0.698
SD ~	ST	0.021	0.063	0.337	0.736
SD ~	Mt	0.049	0.083	0.588	0.557
SD ~	MP	0.302	0.076	4.003	0.000
CWM ~	BT	-0.041	0.076	-0.533	0.594
CWM ~	MT	0.093	0.068	1.37	0.171
CWM ~	ST	0.163	0.072	2.276	0.023
CWM ~	Mt	-0.267	0.093	-2.856	0.004
CWM ~	MP	0.158	0.086	1.837	0.066
BT ~	MT	-0.228	0.061	-3.738	0.000
BT ~	ST	-0.414	0.059	-6.956	0.000
BT ~	Mt	-0.418	0.081	-5.132	0.000
BT ~	MP	0.001	0.08	0.017	0.987
MT ~	ST	-0.148	0.068	-2.155	0.031
MT ~	Mt	-0.272	0.093	-2.932	0.003
MT ~	MP	-0.084	0.093	-0.903	0.367
ST ~	Mt	-0.018	0.096	-0.191	0.849
ST ~	MP	0.057	0.096	0.592	0.554
Mt ~	MP	-0.678	0.052	-12.972	0.000
Chisq	**pvalue**	**Gfi**	**cfi**	**srmr**	**aic**
4.091	0.049	0.91	0.957	0.917	2799.169

Appendix 46 Summary of direct and indirect relationship amongst AGB, CWM, SR, BTSSD, MTSSD, STSSD, Mt, and MP in the natural forests of Pakistan (Figure 45 A).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.lv	std. all
AGB	~	SD	-0.012	0.017	-0.726	0.468	-0.046	0.021	-0.012	-0.046
AGB	~	CWM	0.01	0.017	0.627	0.531	-0.022	0.043	0.01	0.039
AGB	~	BT	0.195	0.016	11.888	0	0.163	0.227	0.195	0.722
AGB	~	MT	0.076	0.014	5.375	0	0.048	0.104	0.076	0.282
AGB	~	ST	0.009	0.015	0.582	0.56	-0.021	0.038	0.009	0.033
AGB	~	Mt	0.033	0.02	1.646	0.1	-0.006	0.071	0.033	0.121
AGB	~	MP	0.021	0.019	1.144	0.252	-0.015	0.058	0.021	0.08
SD	~	CWM	0.462	0.062	7.507	0	0.341	0.582	0.462	0.463
SD	~	BT	-0.235	0.066	-3.546	0	-0.365	-0.105	-0.235	-0.236
SD	~	MT	-0.023	0.059	-0.388	0.698	-0.139	0.093	-0.023	-0.023
SD	~	ST	0.021	0.063	0.337	0.736	-0.102	0.144	0.021	0.021
SD	~	Mt	0.049	0.083	0.588	0.557	-0.113	0.211	0.049	0.049
SD	~	MP	0.302	0.076	4.003	0	0.154	0.45	0.302	0.303
CWM	~	BT	-0.041	0.076	-0.533	0.594	-0.191	0.109	-0.041	-0.041
CWM	~	MT	0.093	0.068	1.37	0.171	-0.04	0.226	0.093	0.093
CWM	~	ST	0.163	0.072	2.276	0.023	0.023	0.303	0.163	0.163
CWM	~	Mt	-0.267	0.093	-2.856	0.004	-0.45	-0.084	-0.267	-0.267
CWM	~	MP	0.158	0.086	1.837	0.066	-0.011	0.328	0.158	0.158
BT	~	MT	-0.228	0.061	-3.738	0	-0.347	-0.108	-0.228	-0.228
BT	~	ST	-0.414	0.059	-6.956	0	-0.53	-0.297	-0.414	-0.414
BT	~	Mt	-0.418	0.081	-5.132	0	-0.577	-0.258	-0.418	-0.418
BT	~	MP	0.001	0.08	0.017	0.987	-0.155	0.158	0.001	0.001
MT	~	ST	-0.148	0.068	-2.155	0.031	-0.282	-0.013	-0.148	-0.148
MT	~	Mt	-0.272	0.093	-2.932	0.003	-0.454	-0.09	-0.272	-0.272
MT	~	MP	-0.084	0.093	-0.903	0.367	-0.266	0.098	-0.084	-0.084
ST	~	Mt	-0.018	0.096	-0.191	0.849	-0.207	0.17	-0.018	-0.018
ST	~	MP	0.057	0.096	0.592	0.554	-0.132	0.245	0.057	0.057
Mt	~	MP	-0.678	0.052	-12.97	0.000	-0.78	-0.575	-0.678	-0.677
AGB	~~	AGB	0.034	0.003	9.975	0.000	0.028	0.041	0.034	0.473
SD	~~	SD	0.599	0.06	9.975	0.000	0.482	0.717	0.599	0.602
CWM	~~	CWM	0.796	0.08	9.975	0.000	0.639	0.952	0.796	0.797
BT	~~	BT	0.685	0.069	9.975	0.000	0.55	0.819	0.685	0.686
MT	~~	MT	0.928	0.093	9.975	0.000	0.746	1.111	0.928	0.931
ST	~~	ST	0.995	0.1	9.975	0.000	0.799	1.19	0.995	0.995
Mt	~~	Mt	0.542	0.054	9.975	0.000	0.435	0.648	0.542	0.542
MP	~~	MP	0.998	0.000	NA	NA	0.998	0.998	0.998	1.000
AGB	r2	AGB	0.527	NA	NA	NA	NA	NA	NA	NA
SD	r2	SD	0.398	NA	NA	NA	NA	NA	NA	NA
CWM	r2	CWM	0.203	NA	NA	NA	NA	NA	NA	NA
BT	r2	BT	0.314	NA	NA	NA	NA	NA	NA	NA
MT	r2	MT	0.069	NA	NA	NA	NA	NA	NA	NA
ST	r2	ST	0.005	NA	NA	NA	NA	NA	NA	NA
Mt	r2	Mt	0.458	NA	NA	NA	NA	NA	NA	NA

Appendix 47 Summary relationship of the linear SEM for founding the relationship amongst AGB, CWM, SR, BTSSD, MTSSD, STSSD, MRH, and MWP in the natrual forests of Pakistan (Figure 45 B).

Response	**Predictor**	**ß-Value**	**Std. Err**	**z-value**	**P-Value**
AGB ~	SD	-0.007	0.019	-0.375	0.708
AGB ~	CWM	0.012	0.018	0.713	0.476
AGB ~	BT	0.187	0.016	11.352	0.000
AGB ~	MT	0.074	0.014	5.244	0.000
AGB ~	ST	0.006	0.015	0.374	0.708
AGB ~	MRH	-0.031	0.022	-1.403	0.161
AGB ~	MWP	-0.024	0.019	-1.284	0.199
SD ~	CWM	0.254	0.064	3.955	0.000
SD ~	BT	-0.327	0.058	-5.611	0.000
SD ~	MT	-0.084	0.053	-1.583	0.113
SD ~	ST	0.001	0.056	0.023	0.981
SD ~	MRH	0.372	0.081	4.597	0.000
SD ~	MWP	-0.205	0.071	-2.896	0.004
CWM ~	BT	-0.054	0.064	-0.839	0.401
CWM ~	MT	0.032	0.059	0.538	0.591
CWM ~	ST	0.127	0.062	2.057	0.04
CWM ~	MRH	0.596	0.079	7.572	0.000
CWM ~	MWP	-0.011	0.078	-0.135	0.893
BT ~	MT	-0.185	0.063	-2.915	0.004
BT ~	ST	-0.4	0.062	-6.447	0.000
BT ~	MRH	0.094	0.087	1.08	0.28
BT ~	MWP	-0.267	0.084	-3.158	0.002
MT ~	ST	-0.158	0.068	-2.312	0.021
MT ~	MRH	0.287	0.095	3.02	0.003
MT ~	MWP	0.093	0.094	0.982	0.326
ST ~	MRH	0.115	0.098	1.177	0.239
ST ~	MWP	0.048	0.098	0.493	0.622
MRH ~	MWP	-0.686	0.051	-13.404	0.000
Chisq	**p-value**	**gfi**	**cfi**	**srmr**	**aic**
4.201	0.053	0.898	0.968	0.918	2906.271

Appendix 48 Summary of direct and indirect relation nship amongst AGB, CWM, SR, BTSSD, MTSSD, STSSD, MRH, and MWP in the natural forests of Pakistan (Figure 45 B).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.lv	std. all
AGB	~	SD	-0.007	0.019	-0.375	0.708	-0.044	0.03	-0.007	-0.026
AGB	~	CWM	0.012	0.018	0.713	0.476	-0.022	0.047	0.012	0.046
AGB	~	BT	0.187	0.016	11.352	0	0.155	0.219	0.187	0.694
AGB	~	MT	0.074	0.014	5.244	0	0.046	0.101	0.074	0.273
AGB	~	ST	0.006	0.015	0.374	0.708	-0.024	0.035	0.006	0.021
AGB	~	MRH	-0.031	0.022	-1.403	0.161	-0.075	0.012	-0.031	-0.116
AGB	~	MWP	-0.024	0.019	-1.284	0.199	-0.062	0.013	-0.024	-0.091
SD	~	CWM	0.254	0.064	3.955	0	0.128	0.38	0.254	0.254
SD	~	BT	-0.327	0.058	-5.611	0	-0.441	-0.213	-0.327	-0.327
SD	~	MT	-0.084	0.053	-1.583	0.113	-0.188	0.02	-0.084	-0.084
SD	~	ST	0.001	0.056	0.023	0.981	-0.109	0.112	0.001	0.001
SD	~	MRH	0.372	0.081	4.597	0	0.213	0.531	0.372	0.371
SD	~	MWP	-0.205	0.071	-2.896	0.004	-0.345	-0.066	-0.205	-0.206
CWM	~	BT	-0.054	0.064	-0.839	0.401	-0.18	0.072	-0.054	-0.054
CWM	~	MT	0.032	0.059	0.538	0.591	-0.083	0.146	0.032	0.031
CWM	~	ST	0.127	0.062	2.057	0.04	0.006	0.248	0.127	0.127
CWM	~	MRH	0.596	0.079	7.572	0	0.442	0.751	0.596	0.594
CWM	~	MWP	-0.011	0.078	-0.135	0.893	-0.164	0.143	-0.011	-0.011
BT	~	MT	-0.185	0.063	-2.915	0.004	-0.309	-0.061	-0.185	-0.185
BT	~	ST	-0.4	0.062	-6.447	0	-0.521	-0.278	-0.4	-0.4
BT	~	MRH	0.094	0.087	1.08	0.28	-0.076	0.264	0.094	0.093
BT	~	MWP	-0.267	0.084	-3.158	0.002	-0.432	-0.101	-0.267	-0.267
MT	~	ST	-0.158	0.068	-2.312	0.021	-0.292	-0.024	-0.158	-0.158
MT	~	MRH	0.287	0.095	3.02	0.003	0.101	0.472	0.287	0.285
MT	~	MWP	0.093	0.094	0.982	0.326	-0.092	0.277	0.093	0.093
ST	~	MRH	0.115	0.098	1.177	0.239	-0.077	0.307	0.115	0.115
ST	~	MWP	0.048	0.098	0.493	0.622	-0.143	0.239	0.048	0.048
MRH	~	MWP	-0.686	0.051	-13.40	0	-0.786	-0.586	-0.686	-0.689
AGB	~~	AGB	0.034	0.003	9.975	0	0.028	0.041	0.034	0.474
SD	~~	SD	0.497	0.05	9.975	0	0.399	0.595	0.497	0.5
CWM	~~	CWM	0.606	0.061	9.975	0	0.487	0.725	0.606	0.608
BT	~~	BT	0.74	0.074	9.975	0	0.594	0.885	0.74	0.742
MT	~~	MT	0.925	0.093	9.975	0	0.743	1.107	0.925	0.928
ST	~~	ST	0.992	0.099	9.975	0	0.797	1.187	0.992	0.992
MRH	~~	MRH	0.52	0.052	9.975	0	0.418	0.622	0.52	0.526
MWP	~~	MWP	0.998	0	NA	NA	0.998	0.998	0.998	1
AGB	r2	AGB	0.526	NA	NA	NA	NA	NA	NA	NA
SD	r2	SD	0.5	NA	NA	NA	NA	NA	NA	NA
CWM	r2	CWM	0.392	NA	NA	NA	NA	NA	NA	NA
BT	r2	BT	0.258	NA	NA	NA	NA	NA	NA	NA
MT	r2	MT	0.072	NA	NA	NA	NA	NA	NA	NA
ST	r2	ST	0.008	NA	NA	NA	NA	NA	NA	NA
MRH	r2	MRH	0.474	NA	NA	NA	NA	NA	NA	NA

Appendix 49 Summary relationship of the linear SEM for founding the relationship amongst AGB, SD, CWM, SSD,BT, clay loam, CNP of whole community in different forest of Pakistan (Figure 52 A).

Response	**Predictor**	**ß-Value**	**Std. Err**	**z-value**	**P-Value**
AGB ~	SD	0.015	0.018	0.868	0.386
AGB ~	CWM	-0.021	0.017	-1.253	0.21
AGB ~	SSD	0.057	0.015	3.916	0
AGB ~	BT	0.137	0.017	8.104	0
AGB ~	Clay loam	0.014	0.015	0.919	0.358
AGB ~	CNP	0.04	0.017	2.351	0.019
SD ~	CWM	0.136	0.067	2.036	0.042
SD ~	SSD	-0.06	0.058	-1.044	0.296
SD ~	BT	0.076	0.067	1.136	0.256
SD ~	Clay loam	0.139	0.058	2.386	0.017
SD ~	CNP	0.047	0.067	0.693	0.488
CWM ~	SSD	0.253	0.058	4.338	0
CWM ~	BT	-0.211	0.069	-3.069	0.002
CWM ~	Clay loam	0.041	0.061	0.665	0.506
CWM ~	CNP	0.204	0.07	2.929	0.003
SSD ~	BT	0.074	0.083	0.884	0.377
SSD ~	Clay loam	0.064	0.074	0.865	0.387
SSD ~	CNP	0.244	0.083	2.944	0.003
BT ~	Clay loam	0.206	0.062	3.352	0.001
BT ~	CNP	0.483	0.062	7.85	0
Clay loam ~	CNP	0.383	0.065	5.865	0
Chisq	**p-value**	**gfi**	**cfi**	**Srmr**	**aic**
4.311	0.057	0.886	0.979	0.919	2420.565

Appendix 50 Summary of direct and indirect relationship amongst AGB, SD, CWM, SSD,BT, clay loam, and CNP of whole community in different forest of Pakistan (Figure 52 A).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.Iv	std. all
AGB	~	SD	0.015	0.018	0.868	0.386	-0.019	0.05	0.015	0.045
AGB	~	CWM	-0.021	0.017	-1.253	0.21	-0.055	0.012	-0.021	-0.068
AGB	~	SSD	0.057	0.015	3.916	0	0.029	0.086	0.057	0.213
AGB	~	BT	0.137	0.017	8.104	0	0.104	0.17	0.137	0.508
AGB	~	Clay loam	0.014	0.015	0.919	0.358	-0.016	0.043	0.014	0.051
AGB	~	CNP	0.04	0.017	2.351	0.019	0.007	0.074	0.04	0.149
SD	~	CWM	0.136	0.067	2.036	0.042	0.005	0.268	0.136	0.149
SD	~	SSD	-0.06	0.058	-1.044	0.296	-0.174	0.053	-0.06	-0.078
SD	~	BT	0.076	0.067	1.136	0.256	-0.055	0.206	0.076	0.098
SD	~	Clay loam	0.139	0.058	2.386	0.017	0.025	0.253	0.139	0.179
SD	~	CNP	0.047	0.067	0.693	0.488	-0.086	0.179	0.047	0.06
CWM	~	SSD	0.253	0.058	4.338	0	0.139	0.367	0.253	0.298
CWM	~	BT	-0.211	0.069	-3.069	0.002	-0.345	-0.076	-0.211	-0.248
CWM	~	Clay loam	0.041	0.061	0.665	0.506	-0.08	0.161	0.041	0.048
CWM	~	CNP	0.204	0.07	2.929	0.003	0.068	0.341	0.204	0.24
SSD	~	BT	0.074	0.083	0.884	0.377	-0.089	0.236	0.074	0.074
SSD	~	Clay loam	0.064	0.074	0.865	0.387	-0.081	0.21	0.064	0.064
SSD	~	CNP	0.244	0.083	2.944	0.003	0.082	0.406	0.244	0.244
BT	~	Clay loam	0.206	0.062	3.352	0.001	0.086	0.327	0.206	0.206
BT	~	CNP	0.483	0.062	7.85	0	0.363	0.604	0.483	0.483
Clay loam	~	CNP	0.383	0.065	5.865	0	0.255	0.511	0.383	0.383
AGB	~~	AGB	0.035	0.003	10	0	0.028	0.041	0.035	0.48
SD	~~	SD	0.543	0.054	10	0	0.437	0.65	0.543	0.908
CWM	~~	CWM	0.606	0.061	10	0	0.487	0.724	0.606	0.842
SSD	~~	SSD	0.891	0.089	10	0	0.716	1.065	0.891	0.895
BT	~~	BT	0.644	0.064	10	0	0.518	0.77	0.644	0.647
Clay loam	~~	Clay loam	0.849	0.085	10	0	0.683	1.015	0.849	0.853
CNP	~~	CNP	0.995	0	NA	NA	0.995	0.995	0.995	1
AGB	r2	AGB	0.52	NA	NA	NA	NA	NA	NA	NA
SD	r2	SD	0.092	NA	NA	NA	NA	NA	NA	NA
CWM	r2	CWM	0.158	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.105	NA	NA	NA	NA	NA	NA	NA
BT	r2	BT	0.353	NA	NA	NA	NA	NA	NA	NA
Clay loam	r2	Clay loam	0.147	NA	NA	NA	NA	NA	NA	NA

Appendix 51 Summary relationship of the linear SEM for founding the relationship amongst AGB, SD, CWM, SSD,BT, SmP, and SMP of whole community in different forest of Pakistan (Figure 52 B).

Response	**Predictor**	**ß-Value**	**Std. Err**	**z-value**	**P-Value**
AGB ~	SD	0.037	0.018	2.062	0.039
AGB ~	CWM	-0.021	0.017	-1.243	0.214
AGB ~	SSD	0.062	0.014	4.315	0
AGB ~	BT	0.148	0.015	10.08	0
AGB ~	SmP	0.045	0.014	3.304	0.001
AGB ~	SMP	-0.02	0.014	-1.425	0.154
SD ~	CWM	0.186	0.064	2.887	0.004
SD ~	SSD	-0.042	0.056	-0.751	0.452
SD ~	BT	0.178	0.056	3.16	0.002
SD ~	SmP	-0.202	0.052	-3.884	0
SD ~	SMP	-0.004	0.055	-0.064	0.949
CWM ~	SSD	0.29	0.058	4.978	0
CWM ~	BT	-0.104	0.061	-1.695	0.09
CWM ~	SmP	0.084	0.057	1.468	0.142
CWM ~	SMP	-0.014	0.06	-0.231	0.817
SSD ~	BT	0.195	0.073	2.664	0.008
SSD ~	SmP	0.055	0.069	0.792	0.428
SSD ~	SMP	-0.1	0.073	-1.374	0.169
BT ~	SmP	0.132	0.066	2.005	0.045
BT ~	SMP	-0.338	0.066	-5.134	0
SmP ~	SMP	0.01	0.071	0.138	0.89
Chisq	**p-value**	**gfi**	**cfi**	**srmr**	**Aic**
4.421	0.061	0.874	0.99	0.92	2514.686

Appendix 52 Summary of direct and indirect relationship amongst AGB, SD, CWM, SSD,BT, SmP, and SMP of whole community in different forest of Pakistan (Figure 52 B).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.lv	std.all
AGB	~	SD	0.037	0.018	2.062	0.039	0.002	0.072	0.037	0.107
AGB	~	CWM	-0.021	0.017	-1.243	0.214	-0.054	0.012	-0.021	-0.06
AGB	~	SSD	0.062	0.014	4.315	0	0.034	0.09	0.062	0.23
AGB	~	BT	0.148	0.015	10.08	0	0.119	0.177	0.148	0.55
AGB	~	SmP	0.045	0.014	3.304	0.001	0.018	0.072	0.045	0.169
AGB	~	SMP	-0.02	0.014	-1.425	0.154	-0.047	0.007	-0.02	-0.07
SD	~	CWM	0.186	0.064	2.887	0.004	0.06	0.312	0.186	0.204
SD	~	SSD	-0.042	0.056	-0.751	0.452	-0.153	0.068	-0.042	-0.05
SD	~	BT	0.178	0.056	3.16	0.002	0.068	0.288	0.178	0.23
SD	~	SmP	-0.202	0.052	-3.884	0	-0.305	-0.1	-0.202	-0.26
SD	~	SMP	-0.004	0.055	-0.064	0.949	-0.111	0.104	-0.004	-0.00
CWM	~	SSD	0.29	0.058	4.978	0	0.176	0.404	0.29	0.341
CWM	~	BT	-0.104	0.061	-1.695	0.09	-0.224	0.016	-0.104	-0.12
CWM	~	SmP	0.084	0.057	1.468	0.142	-0.028	0.195	0.084	0.098
CWM	~	SMP	-0.014	0.06	-0.231	0.817	-0.132	0.104	-0.014	-0.01
SSD	~	BT	0.195	0.073	2.664	0.008	0.052	0.339	0.195	0.195
SSD	~	SmP	0.055	0.069	0.792	0.428	-0.081	0.19	0.055	0.055
SSD	~	SMP	-0.1	0.073	-1.374	0.169	-0.242	0.043	-0.1	-0.1
BT	~	SmP	0.132	0.066	2.005	0.045	0.003	0.261	0.132	0.132
BT	~	SMP	-0.338	0.066	-5.134	0	-0.468	-0.209	-0.338	-0.33
SmP	~	SMP	0.01	0.071	0.138	0.89	-0.129	0.148	0.01	0.01
AGB	~~	AGB	0.034	0.003	10	0	0.027	0.04	0.034	0.469
SD	~~	SD	0.523	0.052	10	0	0.42	0.625	0.523	0.874
CWM	~~	CWM	0.629	0.063	10	0	0.506	0.753	0.629	0.876
SSD	~~	SSD	0.928	0.093	10	0	0.747	1.11	0.928	0.933
BT	~~	BT	0.865	0.086	10	0	0.695	1.034	0.865	0.869
SmP	~~	SmP	0.995	0.099	10	0	0.8	1.19	0.995	1
SMP	~~	SMP	0.995	0	NA	NA	0.995	0.995	0.995	1
AGB	r2	AGB	0.531	NA	NA	NA	NA	NA	NA	NA
SD	r2	SD	0.126	NA	NA	NA	NA	NA	NA	NA
CWM	r2	CWM	0.124	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.067	NA	NA	NA	NA	NA	NA	NA
BT	r2	BT	0.131	NA	NA	NA	NA	NA	NA	NA
SmP	r2	SmP	0	NA	NA	NA	NA	NA	NA	NA

Appendix 53 Summary relationship of the linear SEM for founding the relationship amongst AGB, SD, CWM, SSD,BT, Mt, and MP of whole community in different forest of Pakistan (Figure 53 A).

Response	**Predictor**	**ß-Value**	**Std. Err**	**z-value**	**P-Value**
AGB ~	SD	0.014	0.02	0.688	0.492
AGB ~	CWM	-0.003	0.022	-0.149	0.882
AGB ~	SSD	0.066	0.015	4.411	0
AGB ~	BT	0.168	0.016	10.303	0
AGB ~	Mt	0.023	0.024	0.969	0.333
AGB ~	MP	0.013	0.018	0.702	0.483
SD ~	CWM	0.448	0.069	6.46	0
SD ~	SSD	0.039	0.052	0.759	0.448
SD ~	BT	0.31	0.052	5.934	0
SD ~	Mt	0.525	0.075	6.998	0
SD ~	MP	0.05	0.063	0.793	0.428
CWM ~	SSD	0.128	0.052	2.459	0.014
CWM ~	BT	-0.222	0.051	-4.372	0
CWM ~	Mt	-0.442	0.07	-6.336	0
CWM ~	MP	0.076	0.064	1.183	0.237
SSD ~	BT	0.108	0.068	1.577	0.115
SSD ~	Mt	-0.396	0.09	-4.381	0
SSD ~	MP	-0.041	0.087	-0.472	0.637
BT ~	Mt	-0.346	0.09	-3.842	0
BT ~	MP	0.004	0.09	0.039	0.969
Mt ~	MP	-0.676	0.052	-12.972	0
Chisq	**p-value**	**gfi**	**cfi**	**srmr**	**Aic**
3.321	0.021	0.994	0.88	0.91	2273.519

Appendix 54 Summary of direct and indirect relationship amongst AGB, SD, CWM, SSD,BT, Mt, and MP of whole community in different forest of Pakistan (Figure 53 A).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.Iv	std. all
AGB	~	SD	0.014	0.02	0.688	0.492	-0.026	0.054	0.014	0.04
AGB	~	CWM	-0.003	0.022	-0.149	0.882	-0.046	0.04	-0.003	-0.01
AGB	~	SSD	0.066	0.015	4.411	0	0.037	0.096	0.066	0.246
AGB	~	BT	0.168	0.016	10.303	0	0.136	0.2	0.168	0.625
AGB	~	Mt	0.023	0.024	0.969	0.333	-0.024	0.071	0.023	0.087
AGB	~	MP	0.013	0.018	0.702	0.483	-0.023	0.049	0.013	0.048
SD	~	CWM	0.448	0.069	6.46	0	0.312	0.584	0.448	0.491
SD	~	SSD	0.039	0.052	0.759	0.448	-0.062	0.141	0.039	0.051
SD	~	BT	0.31	0.052	5.934	0	0.208	0.412	0.31	0.4
SD	~	Mt	0.525	0.075	6.998	0	0.378	0.672	0.525	0.677
SD	~	MP	0.05	0.063	0.793	0.428	-0.074	0.174	0.05	0.065
CWM	~	SSD	0.128	0.052	2.459	0.014	0.026	0.231	0.128	0.151
CWM	~	BT	-0.22	0.051	-4.372	0	-0.322	-0.123	-0.222	-0.26
CWM	~	Mt	-0.44	0.07	-6.336	0	-0.579	-0.305	-0.442	-0.52
CWM	~	MP	0.076	0.064	1.183	0.237	-0.05	0.202	0.076	0.09
SSD	~	BT	0.108	0.068	1.577	0.115	-0.026	0.242	0.108	0.108
SSD	~	Mt	-0.39	0.09	-4.381	0	-0.573	-0.219	-0.396	-0.39
SSD	~	MP	-0.04	0.087	-0.472	0.637	-0.212	0.13	-0.041	-0.04
BT	~	Mt	-0.34	0.09	-3.842	0	-0.522	-0.169	-0.346	-0.34
BT	~	MP	0.004	0.09	0.039	0.969	-0.173	0.18	0.004	0.004
Mt	~	MP	-0.67	0.052	-12.97	0	-0.778	-0.574	-0.676	-0.67
AGB	~~	AGB	0.036	0.004	10	0	0.029	0.043	0.036	0.496
SD	~~	SD	0.43	0.043	10	0	0.346	0.514	0.43	0.719
CWM	~~	CWM	0.447	0.045	10	0	0.359	0.534	0.447	0.621
SSD	~~	SSD	0.82	0.082	10	0	0.66	0.981	0.82	0.825
BT	~~	BT	0.875	0.087	10	0	0.703	1.046	0.875	0.879
Mt	~~	Mt	0.54	0.054	10	0	0.434	0.646	0.54	0.543
MP	~~	MP	0.995	0	NA	NA	0.995	0.995	0.995	1
AGB	r2	AGB	0.504	NA	NA	NA	NA	NA	NA	NA
SD	r2	SD	0.281	NA	NA	NA	NA	NA	NA	NA
CWM	r2	CWM	0.379	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.175	NA	NA	NA	NA	NA	NA	NA
BT	r2	BT	0.121	NA	NA	NA	NA	NA	NA	NA
Mt	r2	Mt	0.457	NA	NA	NA	NA	NA	NA	NA

Appendix 55 Summary relationship of the linear SEM for founding the relationship amongst AGB, SD, CWM, SSD,BT, MRH, and MWP of whole community in different forest of Pakistan (Figure 53 B).

Response	**Predictor**	**ß-Value**	**Std. Err**	**z-value**	**P-Value**
AGB ~	SD	0.036	0.019	1.905	0.057
AGB ~	CWM	-0.002	0.021	-0.072	0.943
AGB ~	SSD	0.067	0.015	4.567	0
AGB ~	BT	0.159	0.015	10.575	0
AGB ~	MRH	-0.044	0.023	-1.916	0.055
AGB ~	MWP	-0.033	0.02	-1.627	0.104
SD ~	CWM	0.049	0.079	0.624	0.532
SD ~	SSD	-0.074	0.054	-1.361	0.173
SD ~	BT	0.172	0.054	3.17	0.002
SD ~	MRH	0.415	0.079	5.255	0
SD ~	MWP	0.335	0.07	4.772	0
CWM ~	SSD	0.124	0.048	2.599	0.009
CWM ~	BT	-0.18	0.047	-3.845	0
CWM ~	MRH	0.461	0.063	7.374	0
CWM ~	MWP	-0.113	0.062	-1.806	0.071
SSD ~	BT	0.169	0.068	2.477	0.013
SSD ~	MRH	0.314	0.09	3.493	0
SSD ~	MWP	-0.003	0.092	-0.029	0.977
BT ~	MRH	0.003	0.093	0.029	0.977
BT ~	MWP	-0.3	0.093	-3.225	0.001
MRH ~	MWP	-0.689	0.051	-13.457	0
Chisq	**p-value**	**gfi**	**cfi**	**srmr**	**aic**
4.421	0.061	0.874	0.99	0.92	2514.686

Appendix 56 Summary of direct and indirect relationship amongst AGB, SD, CWM, SSD,BT, MRH, and MWP of whole community in different forest of Pakistan (Figure 53 B).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.lv	std. all
AGB	~	SD	0.036	0.019	1.905	0.057	-0.001	0.074	0.036	0.105
AGB	~	CWM	-0.002	0.021	-0.072	0.943	-0.043	0.04	-0.002	-0.005
AGB	~	SSD	0.067	0.015	4.567	0	0.038	0.096	0.067	0.25
AGB	~	BT	0.159	0.015	10.575	0	0.13	0.188	0.159	0.591
AGB	~	MRH	-0.044	0.023	-1.916	0.055	-0.088	0.001	-0.044	-0.162
AGB	~	MWP	-0.033	0.02	-1.627	0.104	-0.072	0.007	-0.033	-0.121
SD	~	CWM	0.049	0.079	0.624	0.532	-0.106	0.204	0.049	0.054
SD	~	SSD	-0.074	0.054	-1.361	0.173	-0.18	0.033	-0.074	-0.095
SD	~	BT	0.172	0.054	3.17	0.002	0.066	0.279	0.172	0.222
SD	~	MRH	0.415	0.079	5.255	0	0.26	0.569	0.415	0.535
SD	~	MWP	0.335	0.07	4.772	0	0.197	0.473	0.335	0.432
CWM	~	SSD	0.124	0.048	2.599	0.009	0.031	0.218	0.124	0.146
CWM	~	BT	-0.18	0.047	-3.845	0	-0.272	-0.088	-0.18	-0.212
CWM	~	MRH	0.461	0.063	7.374	0	0.339	0.584	0.461	0.543
CWM	~	MWP	-0.113	0.062	-1.806	0.071	-0.235	0.01	-0.113	-0.132
SSD	~	BT	0.169	0.068	2.477	0.013	0.035	0.303	0.169	0.169
SSD	~	MRH	0.314	0.09	3.493	0	0.138	0.49	0.314	0.314
SSD	~	MWP	-0.003	0.092	-0.029	0.977	-0.183	0.178	-0.003	-0.003
BT	~	MRH	0.003	0.093	0.029	0.977	-0.18	0.185	0.003	0.003
BT	~	MWP	-0.3	0.093	-3.225	0.001	-0.482	-0.118	-0.3	-0.3
MRH	~	MWP	-0.689	0.051	-13.457	0	-0.79	-0.589	-0.689	-0.689
AGB	~~	AGB	0.035	0.004	10	0	0.028	0.042	0.035	0.488
SD	~~	SD	0.482	0.048	10	0	0.387	0.576	0.482	0.806
CWM	~~	CWM	0.385	0.039	10	0	0.31	0.461	0.385	0.536
SSD	~~	SSD	0.845	0.084	10	0	0.679	1.01	0.845	0.849
BT	~~	BT	0.904	0.09	10	0	0.727	1.082	0.904	0.909
MRH	~~	MRH	0.522	0.052	10	0	0.42	0.625	0.522	0.525
MWP	~~	MWP	0.995	0	NA	NA	0.995	0.995	0.995	1
AGB	r2	AGB	0.512	NA	NA	NA	NA	NA	NA	NA
SD	r2	SD	0.194	NA	NA	NA	NA	NA	NA	NA
CWM	r2	CWM	0.464	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.151	NA	NA	NA	NA	NA	NA	NA
BT	r2	BT	0.091	NA	NA	NA	NA	NA	NA	NA
MRH	r2	MRH	0.475	NA	NA	NA	NA	NA	NA	NA

Appendix 57 Summary relationship of the linear SEM for founding the relationship amongst AGB, SD, CWM, SSD,BT, clay loam, and CNP of overstorey in different forest of Pakistan (Figure 54 A).

Response	**Predictor**	**ß-Value**	**Std. Err**	**z-value**	**P-Value**
AGB ~	SD	-0.023	0.016	-1.425	0.154
AGB ~	CWM	0.01	0.017	0.629	0.53
AGB ~	SSD	-0.004	0.074	-0.053	0.957
AGB ~	BT	0.143	0.017	8.209	0
AGB ~	Clay loam	0.02	0.015	1.288	0.198
AGB ~	CNP	0.052	0.018	2.917	0.004
SD ~	CWM	0.516	0.062	8.284	0
SD ~	SSD	0.157	0.322	0.486	0.627
SD ~	BT	-0.075	0.076	-0.983	0.326
SD ~	Clay loam	0.054	0.066	0.823	0.411
SD ~	CNP	0.07	0.077	0.908	0.364
CWM ~	SSD	-0.347	0.364	-0.952	0.341
CWM ~	BT	-0.287	0.084	-3.43	0.001
CWM ~	Clay loam	0.025	0.075	0.331	0.741
CWM ~	CNP	0.352	0.084	4.204	0
SSD ~	BT	-0.006	0.016	-0.378	0.705
SSD ~	Clay loam	-0.013	0.015	-0.923	0.356
SSD ~	CNP	0.025	0.016	1.55	0.121
BT ~	Clay loam	0.206	0.062	3.352	0.001
BT ~	CNP	0.483	0.062	7.85	0
Clay loam ~	CNP	0.383	0.065	5.865	0
Chisq	**p-value**	**gfi**	**cfi**	**srmr**	**aic**
3.432	0.011	0.884	0.98	0.911	1909.739

Appendix 58 Summary of direct and indirect relationship amongst AGB, SD, CWM, SSD,BT, MRH, and MWP of whole overstorey in different forest of Pakistan (Figure 54 A).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.Iv	std. all
AGB	~	SD	-0.023	0.016	-1.425	0.154	-0.055	0.009	-0.023	-0.086
AGB	~	CWM	0.01	0.017	0.629	0.53	-0.022	0.043	0.01	0.039
AGB	~	SSD	-0.004	0.074	-0.053	0.957	-0.149	0.141	-0.004	-0.003
AGB	~	BT	0.143	0.017	8.209	0	0.109	0.178	0.143	0.533
AGB	~	Clay loam	0.02	0.015	1.288	0.198	-0.01	0.049	0.02	0.073
AGB	~	CNP	0.052	0.018	2.917	0.004	0.017	0.087	0.052	0.192
SD	~	CWM	0.516	0.062	8.284	0	0.394	0.639	0.516	0.516
SD	~	SSD	0.157	0.322	0.486	0.627	-0.475	0.788	0.157	0.029
SD	~	BT	-0.075	0.076	-0.983	0.326	-0.223	0.074	-0.075	-0.075
SD	~	Clay loam	0.054	0.066	0.823	0.411	-0.075	0.184	0.054	0.054
SD	~	CNP	0.07	0.077	0.908	0.364	-0.081	0.221	0.07	0.07
CWM	~	SSD	-0.347	0.364	-0.952	0.341	-1.061	0.368	-0.347	-0.064
CWM	~	BT	-0.287	0.084	-3.43	0.001	-0.451	-0.123	-0.287	-0.287
CWM	~	Clay loam	0.025	0.075	0.331	0.741	-0.122	0.172	0.025	0.025
CWM	~	CNP	0.352	0.084	4.204	0	0.188	0.516	0.352	0.352
SSD	~	BT	-0.006	0.016	-0.378	0.705	-0.038	0.026	-0.006	-0.033
SSD	~	Clay loam	-0.013	0.015	-0.923	0.356	-0.042	0.015	-0.013	-0.072
SSD	~	CNP	0.025	0.016	1.55	0.121	-0.007	0.057	0.025	0.135
BT	~	Clay loam	0.206	0.062	3.352	0.001	0.086	0.327	0.206	0.206
BT	~	CNP	0.483	0.062	7.85	0	0.363	0.604	0.483	0.483
Clay loam	~	CNP	0.383	0.065	5.865	0	0.255	0.511	0.383	0.383
AGB	~~	AGB	0.037	0.004	10	0	0.03	0.044	0.037	0.513
SD	~~	SD	0.7	0.07	10	0	0.563	0.837	0.7	0.703
CWM	~~	CWM	0.9	0.09	10	0	0.724	1.077	0.9	0.905
SSD	~~	SSD	0.034	0.003	10	0	0.027	0.041	0.034	0.986
BT	~~	BT	0.644	0.064	10	0	0.518	0.77	0.644	0.647
Clay loam	~~	Clay loam	0.849	0.085	10	0	0.683	1.015	0.849	0.853
CNP	~~	CNP	0.995	0	NA	NA	0.995	0.995	0.995	1
AGB	r2	AGB	0.487	NA	NA	NA	NA	NA	NA	NA
SD	r2	SD	0.297	NA	NA	NA	NA	NA	NA	NA
CWM	r2	CWM	0.095	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.014	NA	NA	NA	NA	NA	NA	NA
BT	r2	BT	0.353	NA	NA	NA	NA	NA	NA	NA
Clay loam	r2	Clay loam	0.147	NA	NA	NA	NA	NA	NA	NA

Appendix 59 Summary relationship of the linear SEM for founding the relationship amongst AGB, SD, CWM, SSD,BT, SmP, and SMP of overstorey in different forest of Pakistan (Figure 54 B).

Response	**Predictor**	**ß-Value**	**Std. Err**	**z-value**	**P-Value**
OAGB ~	SD	0.018	0.083	0.213	0.832
OAGB ~	CWM	0.044	0.081	0.543	0.587
OAGB ~	SSD	-0.01	0.367	-0.026	0.979
OAGB ~	BT	0.229	0.073	3.138	0.002
OAGB ~	SmP	0.111	0.07	1.576	0.115
OAGB ~	SMP	-0.04	0.072	-0.545	0.586
SD ~	CWM	0.532	0.058	9.126	0
CWM	SSD	0.257	0.314	0.821	0.412
SSD	BT	-0.014	0.062	-0.224	0.822
BT	SmP	-0.175	0.059	-2.969	0.003
SmP	SMP	-0.07	0.062	-1.133	0.257
CWM ~	SSD	-0.187	0.38	-0.493	0.622
SSD	BT	-0.079	0.076	-1.042	0.297
BT	SmP	-0.028	0.071	-0.396	0.692
SmP	SMP	-0.009	0.075	-0.114	0.909
SSD ~	BT	0.003	0.014	0.225	0.822
BT	SmP	0.013	0.013	0.978	0.328
SmP	SMP	0.006	0.014	0.453	0.651
BT ~	SmP	0.132	0.066	2.005	0.045
SmP	SMP	-0.338	0.066	-5.134	0
SmP ~	SMP	0.01	0.071	0.138	0.89
Chisq	**p-value**	**gfi**	**cfi**	**srmr**	**Aic**
3.431	0.025	0.982	0.891	0.911	2653.967

Appendix 60 Summary of direct and indirect relationship amongst AGB, SD, CWM, SSD,BT, SmP, and SMP of overstorey in different forest of Pakistan (Figure 54 B).

Response	**OP**	**Predictor**	**ß-Value**	**SE**	**Z-Value**	**P-value**	**Ci.lower**	**Ci.upper**	**std.Iv**	**std.all**
OAGB	~	SD	0.018	0.083	0.213	0.832	-0.144	0.18	0.018	0.018
OAGB	~	CWM	0.044	0.081	0.543	0.587	-0.115	0.203	0.044	0.044
OAGB	~	SSD	-0.01	0.367	-0.026	0.979	-0.729	0.71	-0.01	-0.002
OAGB	~	BT	0.229	0.073	3.138	0.002	0.086	0.372	0.229	0.229
OAGB	~	SmP	0.111	0.07	1.576	0.115	-0.027	0.248	0.111	0.111
OAGB	~	SMP	-0.04	0.072	-0.545	0.586	-0.182	0.103	-0.04	-0.04
SD	~	CWM	0.532	0.058	9.126	0	0.418	0.647	0.532	0.532
SD	~	SSD	0.257	0.314	0.821	0.412	-0.357	0.872	0.257	0.048
SD	~	BT	-0.014	0.062	-0.224	0.822	-0.136	0.108	-0.014	-0.014
SD	~	SmP	-0.175	0.059	-2.969	0.003	-0.29	-0.059	-0.175	-0.175
SD	~	SMP	-0.07	0.062	-1.133	0.257	-0.191	0.051	-0.07	-0.07
CWM	~	SSD	-0.187	0.38	-0.493	0.622	-0.932	0.557	-0.187	-0.035
CWM	~	BT	-0.079	0.076	-1.042	0.297	-0.227	0.069	-0.079	-0.079
CWM	~	SmP	-0.028	0.071	-0.396	0.692	-0.168	0.111	-0.028	-0.028
CWM	~	SMP	-0.009	0.075	-0.114	0.909	-0.155	0.138	-0.009	-0.009
SSD	~	BT	0.003	0.014	0.225	0.822	-0.024	0.031	0.003	0.017
SSD	~	SmP	0.013	0.013	0.978	0.328	-0.013	0.039	0.013	0.07
SSD	~	SMP	0.006	0.014	0.453	0.651	-0.021	0.034	0.006	0.034
BT	~	SmP	0.132	0.066	2.005	0.045	0.003	0.261	0.132	0.132
BT	~	SMP	-0.338	0.066	-5.134	0	-0.468	-0.209	-0.338	-0.338
SmP	~	SMP	0.01	0.071	0.138	0.89	-0.129	0.148	0.01	0.01
OAGB	~~	OAGB	0.917	0.092	10	0	0.737	1.096	0.917	0.921
SD	~~	SD	0.671	0.067	10	0	0.54	0.803	0.671	0.674
CWM	~~	CWM	0.986	0.099	10	0	0.793	1.18	0.986	0.991
SSD	~~	SSD	0.034	0.003	10	0	0.027	0.041	0.034	0.994
BT	~~	BT	0.865	0.086	10	0	0.695	1.034	0.865	0.869
SmP	~~	SmP	0.995	0.099	10	0	0.8	1.19	0.995	1
SMP	~~	SMP	0.995	0	NA	NA	0.995	0.995	0.995	1
OAGB	r2	OAGB	0.079	NA	NA	NA	NA	NA	NA	NA
SD	r2	SD	0.326	NA	NA	NA	NA	NA	NA	NA
CWM	r2	CWM	0.009	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.006	NA	NA	NA	NA	NA	NA	NA
BT	r2	BT	0.131	NA	NA	NA	NA	NA	NA	NA
SmP	r2	SmP	0	NA	NA	NA	NA	NA	NA	NA

Appendix 61 Summary relationship of the linear SEM for founding the relationship amongst AGB, SD, CWM, SSD,BT, MP, and Mt of overstorey in different forest of Pakistan (Figure 55 A).

Response	**Predictor**	**ß-Value**	**Std. Err**	**z-value**	**P-Value**
OAGB ~	SD	0.012	0.083	0.141	0.888
OAGB ~	CWM	0.028	0.09	0.307	0.759
OAGB ~	SSD	0.017	0.368	0.045	0.964
OAGB ~	BT	0.231	0.075	3.102	0.002
OAGB ~	MP	-0.026	0.098	-0.259	0.796
OAGB ~	Mt	-0.085	0.099	-0.86	0.39
SD ~	CWM	0.557	0.065	8.549	0
SD ~	SSD	0.212	0.311	0.679	0.497
SD ~	BT	0.049	0.063	0.77	0.441
SD ~	MP	0.173	0.083	2.092	0.036
SD ~	Mt	0.289	0.082	3.537	0
CWM ~	SSD	-0.161	0.338	-0.475	0.635
CWM ~	BT	-0.209	0.067	-3.124	0.002
CWM ~	MP	0.395	0.085	4.637	0
CWM ~	Mt	-0.103	0.088	-1.17	0.242
SSD ~	BT	0.002	0.014	0.163	0.871
SSD ~	MP	-0.008	0.018	-0.462	0.644
SSD ~	Mt	-0.007	0.018	-0.37	0.711
SSD ~	MP	0.004	0.09	0.039	0.969
SSD ~	Mt	-0.346	0.09	-3.842	0
MP ~	Mt	-0.676	0.052	-12.972	0
Chisq	**p-value**	**gfi**	**Cfi**	**srmr**	**Aic**
3.321	0.021	0.994	0.88	0.91	2489.025

Appendix 62 Summary of direct and indirect relationship amongst AGB, SD, CWM, SSD,BT, MP, and Mt of overstorey in different forest of Pakistan (Figure 55 A).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.lv	std.all
OAGB	~	SD	0.012	0.083	0.141	0.888	-0.152	0.175	0.012	0.012
OAGB	~	CWM	0.028	0.09	0.307	0.759	-0.148	0.204	0.028	0.028
OAGB	~	SSD	0.017	0.368	0.045	0.964	-0.704	0.737	0.017	0.003
OAGB	~	BT	0.231	0.075	3.102	0.002	0.085	0.378	0.231	0.231
OAGB	~	MP	-0.026	0.098	-0.259	0.796	-0.219	0.168	-0.026	-0.026
OAGB	~	Mt	-0.085	0.099	-0.86	0.39	-0.28	0.109	-0.085	-0.085
SD	~	CWM	0.557	0.065	8.549	0	0.429	0.685	0.557	0.557
SD	~	SSD	0.212	0.311	0.679	0.497	-0.399	0.822	0.212	0.039
SD	~	BT	0.049	0.063	0.77	0.441	-0.075	0.172	0.049	0.049
SD	~	MP	0.173	0.083	2.092	0.036	0.011	0.335	0.173	0.173
SD	~	Mt	0.289	0.082	3.537	0	0.129	0.448	0.289	0.289
CWM	~	SSD	-0.161	0.338	-0.475	0.635	-0.823	0.502	-0.161	-0.03
CWM	~	BT	-0.209	0.067	-3.124	0.002	-0.34	-0.078	-0.209	-0.209
CWM	~	MP	0.395	0.085	4.637	0	0.228	0.562	0.395	0.395
CWM	~	Mt	-0.103	0.088	-1.17	0.242	-0.276	0.07	-0.103	-0.103
SSD	~	BT	0.002	0.014	0.163	0.871	-0.025	0.03	0.002	0.012
SSD	~	MP	-0.008	0.018	-0.462	0.644	-0.043	0.027	-0.008	-0.044
SSD	~	Mt	-0.007	0.018	-0.37	0.711	-0.043	0.029	-0.007	-0.037
BT	~	MP	0.004	0.09	0.039	0.969	-0.173	0.18	0.004	0.004
BT	~	Mt	-0.346	0.09	-3.842	0	-0.522	-0.169	-0.346	-0.346
MP	~	Mt	-0.676	0.052	-12.972	0	-0.778	-0.574	-0.676	-0.676
OAGB	~~	OAGB	0.925	0.093	10	0	0.744	1.107	0.925	0.93
SD	~~	SD	0.665	0.066	10	0	0.534	0.795	0.665	0.668
CWM	~~	CWM	0.783	0.078	10	0	0.63	0.937	0.783	0.787
SSD	~~	SSD	0.034	0.003	10	0	0.028	0.041	0.034	0.999
BT	~~	BT	0.875	0.087	10	0	0.703	1.046	0.875	0.879
MP	~~	MP	0.54	0.054	10	0	0.434	0.646	0.54	0.543
Mt	~~	Mt	0.995	0	NA	NA	0.995	0.995	0.995	1
OAGB	r2	OAGB	0.07	NA	NA	NA	NA	NA	NA	NA
SD	r2	SD	0.332	NA	NA	NA	NA	NA	NA	NA
CWM	r2	CWM	0.213	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.001	NA	NA	NA	NA	NA	NA	NA
BT	r2	BT	0.121	NA	NA	NA	NA	NA	NA	NA
MP	r2	MP	0.457	NA	NA	NA	NA	NA	NA	NA

Appendix 63 Summary relationship of the linear SEM for founding the relationship amongst AGB, SD, CWM, SSD,BT, MRH, and MWP of overstorey in different forest of Pakistan (Figure 55 B).

Response	Predictor	ß-Value	Std. Err	z-value	P-Value
AGB ~	SD	-0.018	0.018	-0.997	0.319
AGB ~	CWM	0.016	0.019	0.83	0.407
AGB ~	SSD	0.017	0.076	0.226	0.821
AGB ~	BT	0.177	0.015	11.451	0
AGB ~	MWP	-0.015	0.021	-0.738	0.46
AGB ~	MRH	-0.005	0.022	-0.21	0.834
SD ~	CWM	0.375	0.072	5.182	0
SD ~	SSD	0.165	0.302	0.547	0.584
SD ~	BT	-0.071	0.062	-1.153	0.249
SD ~	MWP	0.127	0.083	1.529	0.126
SD ~	MRH	0.403	0.082	4.896	0
CWM ~	SSD	-0.11	0.295	-0.374	0.708
CWM ~	BT	-0.258	0.057	-4.494	0
CWM ~	MWP	-0.327	0.078	-4.219	0
CWM ~	MRH	0.381	0.076	5.037	0
SSD ~	BT	0.005	0.014	0.331	0.741
SSD ~	MWP	0.007	0.019	0.367	0.714
SSD ~	MRH	0.001	0.018	0.056	0.956
BT ~	MWP	-0.3	0.093	-3.225	0.001
BT ~	MRH	0.003	0.093	0.029	0.977
MWP ~	MRH	-0.689	0.051	-13.457	0
Chisq	**p-value**	**gfi**	**cfi**	**srmr**	**aic**
3.211	0.017	1.006	0.869	0.909	1790.218

Appendix 64 Summary of direct and indirect relationship amongst AGB, SD, CWM, SSD,BT, MWP, and MRH of overstorey in different forest of Pakistan (Figure 55 B).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.Iv	std. all
AGB	~	SD	-0.018	0.018	-0.997	0.319	-0.052	0.017	-0.018	-0.065
AGB	~	CWM	0.016	0.019	0.83	0.407	-0.022	0.054	0.016	0.059
AGB	~	SSD	0.017	0.076	0.226	0.821	-0.131	0.165	0.017	0.012
AGB	~	BT	0.177	0.015	11.451	0	0.147	0.208	0.177	0.659
AGB	~	MWP	-0.015	0.021	-0.738	0.46	-0.056	0.025	-0.015	-0.057
AGB	~	MRH	-0.005	0.022	-0.21	0.834	-0.047	0.038	-0.005	-0.017
SD	~	CWM	0.375	0.072	5.182	0	0.233	0.517	0.375	0.375
SD	~	SSD	0.165	0.302	0.547	0.584	-0.427	0.758	0.165	0.031
SD	~	BT	-0.071	0.062	-1.153	0.249	-0.192	0.05	-0.071	-0.071
SD	~	MWP	0.127	0.083	1.529	0.126	-0.036	0.29	0.127	0.127
SD	~	MRH	0.403	0.082	4.896	0	0.241	0.564	0.403	0.403
CWM	~	SSD	-0.11	0.295	-0.374	0.708	-0.689	0.468	-0.11	-0.021
CWM	~	BT	-0.258	0.057	-4.494	0	-0.371	-0.146	-0.258	-0.258
CWM	~	MWP	-0.327	0.078	-4.219	0	-0.479	-0.175	-0.327	-0.327
CWM	~	MRH	0.381	0.076	5.037	0	0.233	0.529	0.381	0.381
SSD	~	BT	0.005	0.014	0.331	0.741	-0.022	0.032	0.005	0.025
SSD	~	MWP	0.007	0.019	0.367	0.714	-0.03	0.043	0.007	0.037
SSD	~	MRH	0.001	0.018	0.056	0.956	-0.035	0.037	0.001	0.005
BT	~	MWP	-0.3	0.093	-3.225	0.001	-0.482	-0.118	-0.3	-0.3
BT	~	MRH	0.003	0.093	0.029	0.977	-0.18	0.185	0.003	0.003
MWP	~	MRH	-0.689	0.051	-13.45	0	-0.79	-0.589	-0.689	-0.689
AGB	~~	AGB	0.039	0.004	10	0	0.031	0.047	0.039	0.542
SD	~~	SD	0.627	0.063	10	0	0.504	0.75	0.627	0.63
CWM	~~	CWM	0.597	0.06	10	0	0.48	0.714	0.597	0.6
SSD	~~	SSD	0.034	0.003	10	0	0.028	0.041	0.034	0.999
BT	~~	BT	0.904	0.09	10	0	0.727	1.082	0.904	0.909
MWP	~~	MWP	0.522	0.052	10	0	0.42	0.625	0.522	0.525
MRH	~~	MRH	0.995	0	NA	NA	0.995	0.995	0.995	1
AGB	r2	AGB	0.458	NA	NA	NA	NA	NA	NA	NA
SD	r2	SD	0.37	NA	NA	NA	NA	NA	NA	NA
CWM	r2	CWM	0.4	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.001	NA	NA	NA	NA	NA	NA	NA
BT	r2	BT	0.091	NA	NA	NA	NA	NA	NA	NA
MWP	r2	MWP	0.475	NA	NA	NA	NA	NA	NA	NA

Appendix 65 Summary relationship of the linear SEM for founding the relationship amongst AGB, SD, CWM, SSD,BT, clay loam, and CNP of understorey in different forest of Pakistan (Figure 56 A).

Response	Predictor	ß-Value	Std. Err	z-value	P-Value
AGB ~	SD	-0.016	0.018	-0.894	0.371
AGB ~	CWM	0.02	0.017	1.157	0.247
AGB ~	SSD	-0.013	0.017	-0.756	0.449
AGB ~	BT	0.141	0.018	7.963	0
AGB ~	Clay loam	0.02	0.015	1.286	0.198
AGB ~	CNP	0.052	0.017	3.007	0.003
SD ~	CWM	0.371	0.064	5.842	0
SD ~	SSD	0.311	0.064	4.874	0
SD ~	BT	-0.25	0.068	-3.702	0
SD ~	Clay loam	0.053	0.06	0.878	0.38
SD ~	CNP	0.09	0.067	1.33	0.184
CWM ~	SSD	0.516	0.061	8.441	0
CWM ~	BT	-0.006	0.075	-0.085	0.932
CWM ~	Clay loam	0.014	0.067	0.216	0.829
CWM ~	CNP	0.06	0.075	0.795	0.426
SSD ~	BT	-0.142	0.087	-1.635	0.102
SSD ~	Clay loam	0.09	0.078	1.161	0.246
SSD ~	CNP	0.156	0.086	1.806	0.071
BT ~	Clay loam	0.208	0.062	3.372	0.001
BT ~	CNP	0.482	0.062	7.828	0
Clay loam ~	CNP	0.383	0.065	5.855	0
Chisq	**p-value**	**Gfi**	**cfi**	**srmr**	**aic**
3.101	0.013	1.018	0.858	0.908	2487.568

Appendix 66 Summary of direct and indirect relationship amongst AGB, SD, CWM, SSD,BT, clay loam, and CNP of understorey in different forest of Pakistan (Figure 56 A).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.Iv	std. all
AGB	~	SD	-0.016	0.018	-0.894	0.371	-0.051	0.019	-0.016	-0.05
AGB	~	CWM	0.02	0.017	1.157	0.247	-0.014	0.054	0.02	0.075
AGB	~	SSD	-0.013	0.017	-0.756	0.449	-0.046	0.021	-0.013	-0.04
AGB	~	BT	0.141	0.018	7.963	0	0.106	0.176	0.141	0.523
AGB	~	Clay loam	0.02	0.015	1.286	0.198	-0.01	0.05	0.02	0.073
AGB	~	CNP	0.052	0.017	3.007	0.003	0.018	0.085	0.052	0.191
SD	~	CWM	0.371	0.064	5.842	0	0.247	0.496	0.371	0.372
SD	~	SSD	0.311	0.064	4.874	0	0.186	0.436	0.311	0.312
SD	~	BT	-0.25	0.068	-3.702	0	-0.383	-0.118	-0.25	-0.21
SD	~	Clay loam	0.053	0.06	0.878	0.38	-0.065	0.171	0.053	0.053
SD	~	CNP	0.09	0.067	1.33	0.184	-0.043	0.222	0.09	0.09
CWM	~	SSD	0.516	0.061	8.441	0	0.396	0.635	0.516	0.516
CWM	~	BT	-0.006	0.075	-0.085	0.932	-0.154	0.141	-0.006	-0.00
CWM	~	Clay loam	0.014	0.067	0.216	0.829	-0.117	0.146	0.014	0.015
CWM	~	CNP	0.06	0.075	0.795	0.426	-0.087	0.207	0.06	0.06
SSD	~	BT	-0.142	0.087	-1.635	0.102	-0.313	0.028	-0.142	-0.14
SSD	~	Clay loam	0.09	0.078	1.161	0.246	-0.062	0.243	0.09	0.09
SSD	~	CNP	0.156	0.086	1.806	0.071	-0.013	0.326	0.156	0.156
BT	~	Clay loam	0.208	0.062	3.372	0.001	0.087	0.329	0.208	0.208
BT	~	CNP	0.482	0.062	7.828	0	0.362	0.603	0.482	0.483
Clay loam	~	CNP	0.383	0.065	5.855	0	0.255	0.512	0.383	0.383
AGB	~~	AGB	0.037	0.004	9.975	0	0.03	0.044	0.037	0.512
SD	~~	SD	0.579	0.058	9.975	0	0.465	0.693	0.579	0.582
CWM	~~	CWM	0.72	0.072	9.975	0	0.579	0.862	0.72	0.722
SSD	~~	SSD	0.97	0.097	9.975	0	0.779	1.16	0.97	0.971
BT	~~	BT	0.645	0.065	9.975	0	0.518	0.771	0.645	0.646
Clay loam	~~	Clay loam	0.853	0.085	9.975	0	0.685	1.02	0.853	0.853
CNP	~~	CNP	1	0	NA	NA	1	1	1	1
AGB	r2	AGB	0.488	NA	NA	NA	NA	NA	NA	NA
SD	r2	SD	0.418	NA	NA	NA	NA	NA	NA	NA
CWM	r2	CWM	0.278	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.029	NA	NA	NA	NA	NA	NA	NA
BT	r2	BT	0.354	NA	NA	NA	NA	NA	NA	NA
Clay loam	r2	Clay loam	0.147	NA	NA	NA	NA	NA	NA	NA

Appendix 67 Summary relationship of the linear SEM for founding the relationship amongst AGB, SD, CWM, SSD,BT, SmP, and SMP of understorey in different forest of Pakistan (Figure 56 B).

Response	**Predictor**	**ß-Value**	**Std. Err**	**Z-value**	**P-Value**
AGB ~	SD	-0.007	0.018	-0.377	0.706
AGB ~	CWM	0.02	0.017	1.136	0.256
AGB ~	SSD	-0.011	0.017	-0.641	0.521
AGB ~	BT	0.166	0.015	10.93	0
AGB ~	SmP	0.04	0.014	2.846	0.004
AGB ~	SMP	-0.025	0.015	-1.689	0.091
SD ~	CWM	0.372	0.064	5.846	0
SD ~	SSD	0.333	0.064	5.238	0
SD ~	BT	-0.196	0.058	-3.386	0.001
SD ~	SmP	-0.062	0.055	-1.142	0.254
SD ~	SMP	-0.076	0.058	-1.329	0.184
CWM ~	SSD	0.527	0.06	8.73	0
CWM ~	BT	0.019	0.065	0.293	0.769
CWM ~	SmP	-0.02	0.061	-0.322	0.747
CWM ~	SMP	-0.05	0.064	-0.774	0.439
SSD ~	BT	-0.017	0.076	-0.226	0.821
SSD ~	SmP	0.06	0.071	0.847	0.397
SSD ~	SMP	0.028	0.075	0.369	0.712
BT ~	SmP	0.134	0.066	2.03	0.042
BT ~	SMP	-0.338	0.066	-5.128	0
SmP ~	SMP	0.01	0.071	0.136	0.892
Chisq	**p-value**	**gfi**	**Cfi**	**srmr**	**aic**
2.991	0.009	1.03	0.847	0.907	2584.496

Appendix 68 Summary of direct and indirect relationship amongst AGB, SD, CWM, SSD,BT, SmP, and SMP of understorey in different forest of Pakistan (Figure 56 B).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.lv	std. all
AGB	~	SD	-0.007	0.018	-0.377	0.706	-0.042	0.029	-0.007	-0.025
AGB	~	CWM	0.02	0.017	1.136	0.256	-0.014	0.054	0.02	0.074
AGB	~	SSD	-0.011	0.017	-0.641	0.521	-0.045	0.023	-0.011	-0.041
AGB	~	BT	0.166	0.015	10.93	0	0.136	0.195	0.166	0.615
AGB	~	SmP	0.04	0.014	2.846	0.004	0.012	0.067	0.04	0.147
AGB	~	SMP	-0.025	0.015	-1.689	0.091	-0.054	0.004	-0.025	-0.092
SD	~	CWM	0.372	0.064	5.846	0	0.247	0.496	0.372	0.372
SD	~	SSD	0.333	0.064	5.238	0	0.209	0.458	0.333	0.334
SD	~	BT	-0.196	0.058	-3.386	0.001	-0.31	-0.083	-0.196	-0.197
SD	~	SmP	-0.062	0.055	-1.142	0.254	-0.169	0.045	-0.062	-0.063
SD	~	SMP	-0.076	0.058	-1.329	0.184	-0.189	0.036	-0.076	-0.077
CWM	~	SSD	0.527	0.06	8.73	0	0.409	0.645	0.527	0.527
CWM	~	BT	0.019	0.065	0.293	0.769	-0.108	0.146	0.019	0.019
CWM	~	SmP	-0.02	0.061	-0.322	0.747	-0.139	0.1	-0.02	-0.02
CWM	~	SMP	-0.05	0.064	-0.774	0.439	-0.175	0.076	-0.05	-0.05
SSD	~	BT	-0.017	0.076	-0.226	0.821	-0.166	0.132	-0.017	-0.017
SSD	~	SmP	0.06	0.071	0.847	0.397	-0.08	0.2	0.06	0.06
SSD	~	SMP	0.028	0.075	0.369	0.712	-0.12	0.175	0.028	0.028
BT	~	SmP	0.134	0.066	2.03	0.042	0.005	0.263	0.134	0.134
BT	~	SMP	-0.338	0.066	-5.128	0	-0.468	-0.209	-0.338	-0.339
SmP	~	SMP	0.01	0.071	0.136	0.892	-0.129	0.149	0.01	0.01
AGB	~~	AGB	0.037	0.004	9.975	0	0.03	0.045	0.037	0.517
SD	~~	SD	0.579	0.058	9.975	0	0.465	0.693	0.579	0.582
CWM	~~	CWM	0.72	0.072	9.975	0	0.579	0.862	0.72	0.722
SSD	~~	SSD	0.993	0.1	9.975	0	0.798	1.189	0.993	0.995
BT	~~	BT	0.866	0.087	9.975	0	0.696	1.036	0.866	0.868
SmP	~~	SmP	0.999	0.1	9.975	0	0.802	1.195	0.999	1
SMP	~~	SMP	1	0	NA	NA	1	1	1	1
AGB	r2	AGB	0.483	NA	NA	NA	NA	NA	NA	NA
SD	r2	SD	0.418	NA	NA	NA	NA	NA	NA	NA
CWM	r2	CWM	0.278	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.005	NA	NA	NA	NA	NA	NA	NA
BT	r2	BT	0.132	NA	NA	NA	NA	NA	NA	NA
SmP	r2	SmP	0	NA	NA	NA	NA	NA	NA	NA

Appendix 69 Summary relationship of the linear SEM for founding the relationship amongst AGB, SD, CWM, SSD,BT, Mt, and MRH of understorey in different forest of Pakistan (Figure 57 A).

Response	Predictor	ß-Value	Std. Err	z-value	P-Value
AGB ~	SD	-0.012	0.019	-0.636	0.525
AGB ~	CWM	0.02	0.018	1.116	0.265
AGB ~	SSD	-0.01	0.018	-0.548	0.584
AGB ~	BT	0.177	0.016	11.213	0
AGB ~	Mt	0.006	0.021	0.281	0.778
AGB ~	MP	0.015	0.02	0.745	0.457
SD ~	CWM	0.345	0.064	5.419	0
SD ~	SSD	0.286	0.064	4.459	0
SD ~	BT	-0.206	0.057	-3.61	0
SD ~	Mt	0.11	0.077	1.419	0.156
SD ~	MP	0.276	0.072	3.825	0
CWM ~	SSD	0.42	0.065	6.475	0
CWM ~	BT	-0.054	0.063	-0.859	0.39
CWM ~	Mt	-0.186	0.085	-2.185	0.029
CWM ~	MP	0.088	0.08	1.102	0.27
SSD ~	BT	-0.174	0.068	-2.556	0.011
SSD ~	Mt	-0.332	0.09	-3.697	0
SSD ~	MP	0.168	0.087	1.943	0.052
BT ~	Mt	-0.349	0.09	-3.869	0
BT ~	MP	-0.001	0.09	-0.013	0.989
Mt ~	MP	-0.678	0.052	-12.972	0
Chisq	**p-value**	**gfi**	**Cfi**	**srmr**	**Aic**
2.881	0.005	1.042	0.836	0.906	2409.61

Appendix 70 Summary of direct and indirect relationship amongst AGB, SD, CWM, SSD,BT, Mt, and MP of understorey in different forest of Pakistan (Figure 57 A).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.lv	std. all
AGB	~	SD	-0.012	0.019	-0.636	0.525	-0.049	0.025	-0.012	-0.045
AGB	~	CWM	0.02	0.018	1.116	0.265	-0.015	0.056	0.02	0.076
AGB	~	SSD	-0.01	0.018	-0.548	0.584	-0.045	0.025	-0.01	-0.037
AGB	~	BT	0.177	0.016	11.213	0	0.146	0.208	0.177	0.657
AGB	~	Mt	0.006	0.021	0.281	0.778	-0.035	0.047	0.006	0.022
AGB	~	MP	0.015	0.02	0.745	0.457	-0.024	0.054	0.015	0.055
SD	~	CWM	0.345	0.064	5.419	0	0.22	0.47	0.345	0.345
SD	~	SSD	0.286	0.064	4.459	0	0.16	0.412	0.286	0.286
SD	~	BT	-0.206	0.057	-3.61	0	-0.317	-0.094	-0.206	-0.206
SD	~	Mt	0.11	0.077	1.419	0.156	-0.042	0.261	0.11	0.11
SD	~	MP	0.276	0.072	3.825	0	0.135	0.417	0.276	0.276
CWM	~	SSD	0.42	0.065	6.475	0	0.293	0.547	0.42	0.42
CWM	~	BT	-0.054	0.063	-0.859	0.39	-0.178	0.07	-0.054	-0.054
CWM	~	Mt	-0.186	0.085	-2.185	0.029	-0.352	-0.019	-0.186	-0.186
CWM	~	MP	0.088	0.08	1.102	0.27	-0.069	0.245	0.088	0.088
SSD	~	BT	-0.174	0.068	-2.556	0.011	-0.307	-0.041	-0.174	-0.174
SSD	~	Mt	-0.332	0.09	-3.697	0	-0.508	-0.156	-0.332	-0.332
SSD	~	MP	0.168	0.087	1.943	0.052	-0.001	0.338	0.168	0.168
BT	~	Mt	-0.349	0.09	-3.869	0	-0.526	-0.172	-0.349	-0.349
BT	~	MP	-0.001	0.09	-0.013	0.989	-0.178	0.176	-0.001	-0.001
Mt	~	MP	-0.678	0.052	-12.972	0	-0.78	-0.575	-0.678	-0.677
AGB	~~	AGB	0.039	0.004	9.975	0	0.032	0.047	0.039	0.543
SD	~~	SD	0.546	0.055	9.975	0	0.439	0.653	0.546	0.549
CWM	~~	CWM	0.677	0.068	9.975	0	0.544	0.81	0.677	0.678
SSD	~~	SSD	0.808	0.081	9.975	0	0.649	0.967	0.808	0.809
BT	~~	BT	0.876	0.088	9.975	0	0.704	1.049	0.876	0.879
Mt	~~	Mt	0.542	0.054	9.975	0	0.435	0.648	0.542	0.542
MP	~~	MP	0.998	0	NA	NA	0.998	0.998	0.998	1
AGB	r2	AGB	0.457	NA	NA	NA	NA	NA	NA	NA
SD	r2	SD	0.451	NA	NA	NA	NA	NA	NA	NA
CWM	r2	CWM	0.322	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.191	NA	NA	NA	NA	NA	NA	NA
BT	r2	BT	0.121	NA	NA	NA	NA	NA	NA	NA
Mt	r2	Mt	0.458	NA	NA	NA	NA	NA	NA	NA

Appendix 71 Summary relationship of the linear SEM for founding the relationship amongst AGB, SD, CWM, SSD,BT, MWP, and MRH of understorey in different forest of Pakistan (Figure 57 B).

Response	Predictor	ß-Value	Std. Err	z-value	P-Value
AGB ~	SD	-0.016	0.02	-0.805	0.421
AGB ~	CWM	0.019	0.019	1.008	0.314
AGB ~	SSD	-0.012	0.019	-0.65	0.515
AGB ~	BT	0.171	0.016	10.586	0
AGB ~	MWP	-0.024	0.02	-1.173	0.241
AGB ~	MRH	-0.003	0.025	-0.129	0.898
SD ~	CWM	0.217	0.065	3.353	0.001
SD ~	SSD	0.156	0.065	2.397	0.017
SD ~	BT	-0.296	0.053	-5.57	0
SD ~	MWP	-0.202	0.07	-2.876	0.004
SD ~	MRH	0.279	0.084	3.306	0.001
CWM ~	SSD	0.233	0.069	3.383	0.001
CWM ~	BT	-0.073	0.058	-1.253	0.21
CWM ~	MWP	-0.007	0.077	-0.086	0.931
CWM ~	MRH	0.479	0.086	5.586	0
SSD ~	BT	-0.157	0.058	-2.68	0.007
SSD ~	MWP	-0.051	0.079	-0.644	0.52
SSD ~	MRH	0.599	0.077	7.758	0
BT ~	MWP	-0.302	0.093	-3.234	0.001
BT ~	MRH	-0.002	0.094	-0.021	0.983
MWP ~	MRH	-0.692	0.052	-13.404	0
Chisq	**p-value**	**gfi**	**Cfi**	**Srmr**	**aic**
2.771	0.001	1.054	0.825	0.905	2304.96

Appendix 72 Summary of direct and indirect relationship amongst AGB, SD, CWM, SSD,BT, MWP, and MRH of understorey in different forest of Pakistan (Figure 57 B).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.Iv	std. all
AGB	~	SD	-0.016	0.02	-0.805	0.421	-0.055	0.023	-0.016	-0.06
AGB	~	CWM	0.019	0.019	1.008	0.314	-0.018	0.056	0.019	0.07
AGB	~	SSD	-0.012	0.019	-0.65	0.515	-0.049	0.024	-0.012	-0.045
AGB	~	BT	0.171	0.016	10.586	0	0.139	0.203	0.171	0.635
AGB	~	MWP	-0.024	0.02	-1.173	0.241	-0.064	0.016	-0.024	-0.088
AGB	~	MRH	-0.003	0.025	-0.129	0.898	-0.051	0.045	-0.003	-0.012
SD	~	CWM	0.217	0.065	3.353	0.001	0.09	0.344	0.217	0.218
SD	~	SSD	0.156	0.065	2.397	0.017	0.028	0.283	0.156	0.156
SD	~	BT	-0.296	0.053	-5.57	0	-0.401	-0.192	-0.296	-0.297
SD	~	MWP	-0.202	0.07	-2.876	0.004	-0.34	-0.064	-0.202	-0.203
SD	~	MRH	0.279	0.084	3.306	0.001	0.114	0.445	0.279	0.278
CWM	~	SSD	0.233	0.069	3.383	0.001	0.098	0.369	0.233	0.234
CWM	~	BT	-0.073	0.058	-1.253	0.21	-0.186	0.041	-0.073	-0.073
CWM	~	MWP	-0.007	0.077	-0.086	0.931	-0.157	0.144	-0.007	-0.007
CWM	~	MRH	0.479	0.086	5.586	0	0.311	0.648	0.479	0.478
SSD	~	BT	-0.157	0.058	-2.68	0.007	-0.271	-0.042	-0.157	-0.157
SSD	~	MWP	-0.051	0.079	-0.644	0.52	-0.205	0.104	-0.051	-0.051
SSD	~	MRH	0.599	0.077	7.758	0	0.448	0.751	0.599	0.597
BT	~	MWP	-0.302	0.093	-3.234	0.001	-0.484	-0.119	-0.302	-0.302
BT	~	MRH	-0.002	0.094	-0.021	0.983	-0.185	0.182	-0.002	-0.002
MWP	~	MRH	-0.692	0.052	-13.40	0	-0.793	-0.59	-0.692	-0.689
AGB	~~	AGB	0.039	0.004	9.975	0	0.031	0.047	0.039	0.54
SD	~~	SD	0.49	0.049	9.975	0	0.393	0.586	0.49	0.492
CWM	~~	CWM	0.585	0.059	9.975	0	0.47	0.7	0.585	0.587
SSD	~~	SSD	0.617	0.062	9.975	0	0.496	0.739	0.617	0.618
BT	~~	BT	0.908	0.091	9.975	0	0.729	1.086	0.908	0.91
MWP	~~	MWP	0.524	0.053	9.975	0	0.421	0.627	0.524	0.526
MRH	~~	MRH	0.99	0	NA	NA	0.99	0.99	0.99	1
AGB	r2	AGB	0.46	NA	NA	NA	NA	NA	NA	NA
SD	r2	SD	0.508	NA	NA	NA	NA	NA	NA	NA
CWM	r2	CWM	0.413	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.382	NA	NA	NA	NA	NA	NA	NA
BT	r2	BT	0.09	NA	NA	NA	NA	NA	NA	NA
MWP	r2	MWP	0.474	NA	NA	NA	NA	NA	NA	NA

Appendix 73 Summary relationship of the linear SEM for founding the relationship amongst CO_2, topography, SSD, clay loam, and CNP in different forest of Pakistan (Figure 65 A).

Response	**Predictor**	**ß-Value**	**Std. Err**	**z-value**	**P-Value**
CO2 ~	SSD	0.321	0.067	4.821	0
CO2 ~	Clay loam	0.142	0.06	2.378	0.017
CO2 ~	CNP	0.396	0.068	5.832	0
CO2 ~	Topography	0.132	0.063	2.103	0.035
SSD ~	Clay loam	0.139	0.063	2.206	0.027
SSD ~	CNP	0.176	0.071	2.474	0.013
SSD ~	Topography	-0.072	0.066	-1.083	0.279
Clay loam ~	CNP	0.405	0.075	5.42	0
Clay loam ~	Topography	-0.004	0.075	-0.049	0.961
CNP ~	Topography	0.501	0.061	8.198	0
Chisq	**p-value**	**gfi**	**cfi**	**Srmr**	**aic**
4.531	0.065	0.862	0.911	0.921	2010.91

Appendix 74 Summary of direct and indirect relationship amongst CO_2, topography, SSD, clay loam, and CNP in different forest of Pakistan (Figure 65 A).

Response	**OP**	**Predictor**	**ß-Value**	**SE**	**Z-Value**	**P-value**	**Ci.lower**	**Ci.upper**	**std.Iv**	**std. all**
CO2	~	SSD	0.321	0.067	4.821	0	0.19	0.451	0.321	0.268
CO2	~	Clay loam	0.142	0.06	2.378	0.017	0.025	0.26	0.142	0.14
CO2	~	CNP	0.396	0.068	5.832	0	0.263	0.53	0.396	0.39
CO2	~	Topography	0.132	0.063	2.103	0.035	0.009	0.255	0.132	0.13
SSD	~	Clay loam	0.139	0.063	2.206	0.027	0.015	0.262	0.139	0.163
SSD	~	CNP	0.176	0.071	2.474	0.013	0.037	0.316	0.176	0.208
SSD	~	Topography	-0.072	0.066	-1.083	0.279	-0.202	0.058	-0.072	-0.08
Clay loam	~	CNP	0.405	0.075	5.42	0	0.259	0.552	0.405	0.405
Clay loam	~	Topography	-0.004	0.075	-0.049	0.961	-0.15	0.143	-0.004	-0.00
CNP	~	Topography	0.501	0.061	8.198	0	0.382	0.621	0.501	0.501
CO2	~~	CO2	0.582	0.058	10	0	0.468	0.697	0.582	0.568
SSD	~~	SSD	0.658	0.066	10	0	0.529	0.787	0.658	0.919
Clay loam	~~	Clay loam	0.833	0.083	10	0	0.67	0.996	0.833	0.837
CNP	~~	CNP	0.745	0.074	10	0	0.599	0.891	0.745	0.749
Topography	~~	Topography	0.995	0	NA	NA	0.995	0.995	0.995	1
CO2	r2	CO2	0.432	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.081	NA	NA	NA	NA	NA	NA	NA
Clay loam	r2	Clay loam	0.163	NA	NA	NA	NA	NA	NA	NA
CNP	r2	CNP	0.251	NA	NA	NA	NA	NA	NA	NA

Appendix 75 Summary relationship of the linear SEM for founding the relationship amongst CO_2, topography, SSD, SmP, and SMP in different forest of Pakistan (Figure 65 B).

Response	Predictor	ß-Value	Std. Err	z-value	P-Value
CO2 ~	SR	-0.113	0.039	-2.933	0.003
CO2 ~	SSD	0.331	0.044	7.522	0
CO2 ~	SmP	0.093	0.039	2.405	0.016
CO2 ~	SMP	0.194	0.042	4.633	0
CO2 ~	Topography	0.057	0.012	4.544	0
SR ~	SSD	-0.019	0.08	-0.233	0.815
SR ~	SmP	-0.12	0.07	-1.71	0.087
SR ~	SMP	0.202	0.075	2.696	0.007
SR ~	Topography	0.031	0.023	1.372	0.17
SSD ~	SmP	0.035	0.062	0.561	0.575
SSD ~	SMP	0.036	0.066	0.553	0.58
SSD ~	Topography	0.011	0.02	0.562	0.574
SmP ~	SMP	-0.003	0.075	-0.039	0.969
SmP ~	Topography	-0.073	0.022	-3.289	0.001
SMP ~	Topography	0.124	0.019	6.529	0
Chisq	**p-value**	**gfi**	**cfi**	**srmr**	**aic**
5.411	0.097	0.766	1.891	5.411	2482.373

Appendix 76 Summary of direct and indirect relationship amongst CO_2, topography, SSD, SmP, and SMP in different forests of Pakistan (Figure 65 B).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.Iv	std. all
CO2	~	SR	-0.113	0.039	-2.933	0.003	-0.189	-0.038	-0.113	-0.168
CO2	~	SSD	0.331	0.044	7.522	0	0.245	0.417	0.331	0.411
CO2	~	SmP	0.093	0.039	2.405	0.016	0.017	0.169	0.093	0.136
CO2	~	SMP	0.194	0.042	4.633	0	0.112	0.275	0.194	0.283
CO2	~	Topography	0.057	0.012	4.544	0	0.032	0.081	0.057	0.282
SR	~	SSD	-0.019	0.08	-0.233	0.815	-0.176	0.139	-0.019	-0.016
SR	~	SmP	-0.12	0.07	-1.71	0.087	-0.258	0.018	-0.12	-0.119
SR	~	SMP	0.202	0.075	2.696	0.007	0.055	0.349	0.202	0.2
SR	~	Topography	0.031	0.023	1.372	0.17	-0.013	0.076	0.031	0.104
SSD	~	SmP	0.035	0.062	0.561	0.575	-0.086	0.156	0.035	0.041
SSD	~	SMP	0.036	0.066	0.553	0.58	-0.093	0.166	0.036	0.043
SSD	~	Topography	0.011	0.02	0.562	0.574	-0.028	0.05	0.011	0.045
SmP	~	SMP	-0.003	0.075	-0.039	0.969	-0.151	0.145	-0.003	-0.003
SmP	~	Topography	-0.073	0.022	-3.289	0.001	-0.117	-0.03	-0.073	-0.248
SMP	~	Topography	0.124	0.019	6.529	0	0.086	0.161	0.124	0.419
CO2	~~	CO2	0.276	0.028	10	0	0.222	0.33	0.276	0.594
SR	~~	SR	0.921	0.092	10	0	0.741	1.102	0.921	0.906
SSD	~~	SSD	0.712	0.071	10	0	0.572	0.851	0.712	0.994
SmP	~~	SmP	0.933	0.093	10	0	0.75	1.116	0.933	0.938
SMP	~~	SMP	0.82	0.082	10	0	0.659	0.981	0.82	0.824
Topography	~~	Topography	11.443	0	NA	NA	11.443	11.443	11.443	1
CO2	r2	CO2	0.406	NA	NA	NA	NA	NA	NA	NA
SR	r2	SR	0.094	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.006	NA	NA	NA	NA	NA	NA	NA
SmP	r2	SmP	0.062	NA	NA	NA	NA	NA	NA	NA
SMP	r2	SMP	0.176	NA	NA	NA	NA	NA	NA	NA

Appendix 77 Summary relationship of the linear SEM for founding the relationship amongst CO_2, topography, SSD, Mt, and MP in different forest of Pakistan (Figure 66 A).

Response	Predictor	ß-Value	Std. Err	z-value	P-Value
CO2 ~	SR	-0.12	0.036	-3.34	0.001
CO2 ~	SSD	0.261	0.042	6.155	0
CO2 ~	Mt	0.314	0.054	5.797	0
CO2 ~	MP	0.071	0.049	1.454	0.146
CO2 ~	Topography	0.017	0.023	0.723	0.47
SR ~	SSD	-0.087	0.083	-1.052	0.293
SR ~	Mt	0.202	0.105	1.917	0.055
SR ~	MP	0.176	0.095	1.842	0.066
SR ~	Topography	-0.114	0.045	-2.52	0.012
SSD ~	Mt	0.264	0.088	3.01	0.003
SSD ~	MP	-0.02	0.081	-0.241	0.81
SSD ~	Topography	-0.068	0.038	-1.777	0.076
Mt ~	MP	0.611	0.049	12.433	0
Mt ~	Topography	0.166	0.028	5.832	0
MP ~	Topography	0.181	0.039	4.665	0
Chisq	**p-value**	**gfi**	**Cfi**	**srmr**	**aic**
6.291	0.129	0.67	0.777	6.291	2305.44

Appendix 78 Summary of direct and indirect relationship amongst CO_2, topography, SSD, Mt, and MP in different forests of Pakistan (Figure 66 A).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.Iv	std. all
CO2	~	SR	-0.12	0.036	-3.34	0.001	-0.191	-0.05	-0.12	-0.178
CO2	~	SSD	0.261	0.042	6.155	0	0.178	0.344	0.261	0.324
CO2	~	Mt	0.314	0.054	5.797	0	0.208	0.42	0.314	0.46
CO2	~	MP	0.071	0.049	1.454	0.146	-0.025	0.167	0.071	0.104
CO2	~	Topography	0.017	0.023	0.723	0.47	-0.029	0.063	0.017	0.043
SR	~	SSD	-0.087	0.083	-1.052	0.293	-0.25	0.075	-0.087	-0.073
SR	~	Mt	0.202	0.105	1.917	0.055	-0.005	0.409	0.202	0.2
SR	~	MP	0.176	0.095	1.842	0.066	-0.011	0.363	0.176	0.174
SR	~	Topography	-0.114	0.045	-2.52	0.012	-0.203	-0.025	-0.114	-0.195
SSD	~	Mt	0.264	0.088	3.01	0.003	0.092	0.436	0.264	0.312
SSD	~	MP	-0.02	0.081	-0.241	0.81	-0.179	0.14	-0.02	-0.023
SSD	~	Topography	-0.068	0.038	-1.777	0.076	-0.143	0.007	-0.068	-0.138
Mt	~	MP	0.611	0.049	12.433	0	0.514	0.707	0.611	0.611
Mt	~	Topography	0.166	0.028	5.832	0	0.11	0.222	0.166	0.286
MP	~	Topography	0.181	0.039	4.665	0	0.105	0.258	0.181	0.313
CO2	~~	CO2	0.239	0.024	10	0	0.192	0.286	0.239	0.514
SR	~~	SR	0.922	0.092	10	0	0.741	1.102	0.922	0.907
SSD	~~	SSD	0.668	0.067	10	0	0.537	0.798	0.668	0.933
Mt	~~	Mt	0.433	0.043	10	0	0.348	0.518	0.433	0.435
MP	~~	MP	0.897	0.09	10	0	0.721	1.073	0.897	0.902
Topography	~~	Topography	2.967	0	NA	NA	2.967	2.967	2.967	1
CO2	r2	CO2	0.486	NA	NA	NA	NA	NA	NA	NA
SR	r2	SR	0.093	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.067	NA	NA	NA	NA	NA	NA	NA
Mt	r2	Mt	0.565	NA	NA	NA	NA	NA	NA	NA
MP	r2	MP	0.098	NA	NA	NA	NA	NA	NA	NA

Appendix 79 Summary relationship of the linear SEM for founding the relationship amongst CO_2, topography, SSD, Mt, and MWP in different forest of Pakistan (Figure 66 B).

Response	**Predictor**	**ß-Value**	**Std. Err**	**z-value**	**P-Value**
CO2 ~	SR	0.02	0.029	0.688	0.491
CO2 ~	SSD	0.239	0.047	5.07	0
CO2 ~	MRH	0.438	0.032	13.578	0
CO2 ~	MWP	0.022	0.04	0.548	0.584
CO2 ~	Topography	0.056	0.018	3.156	0.002
SR ~	SSD	0.078	0.116	0.677	0.498
SR ~	MRH	-0.143	0.079	-1.822	0.068
SR ~	MWP	-0.063	0.098	-0.641	0.522
SR ~	Topography	-0.012	0.043	-0.269	0.788
SSD ~	MRH	0.237	0.045	5.255	0
SSD ~	MWP	0.575	0.044	12.978	0
SSD ~	Topography	0.032	0.026	1.199	0.231
MRH ~	MWP	-0.092	0.069	-1.325	0.185
MRH ~	Topography	0.143	0.04	3.572	0
MWP ~	Topography	-0.115	0.04	-2.874	0.004
Chisq	**p-value**	**gfi**	**cfi**	**srmr**	**aic**
7.171	0.100	0.574	1.265	0.971	2292.839

Appendix 80 Summary of direct and indirect relationship amongst CO_2, topography, SSD, MRH, and MWP in different forests of Pakistan (Figure 66 B).

Response	OP	Predictor	ß-Value	SE	Z-Value	P-value	Ci.lower	Ci.upper	std.Iv	std. all
CO2	~	SR	0.02	0.029	0.688	0.491	-0.037	0.076	0.02	0.029
CO2	~	SSD	0.239	0.047	5.07	0	0.147	0.331	0.239	0.297
CO2	~	MRH	0.438	0.032	13.578	0	0.375	0.501	0.438	0.641
CO2	~	MWP	0.022	0.04	0.548	0.584	-0.057	0.101	0.022	0.032
CO2	~	Topography	0.056	0.018	3.156	0.002	0.021	0.09	0.056	0.141
SR	~	SSD	0.078	0.116	0.677	0.498	-0.149	0.305	0.078	0.066
SR	~	MRH	-0.143	0.079	-1.822	0.068	-0.298	0.011	-0.143	-0.142
SR	~	MWP	-0.063	0.098	-0.641	0.522	-0.256	0.13	-0.063	-0.062
SR	~	Topography	-0.012	0.043	-0.269	0.788	-0.097	0.073	-0.012	-0.02
SSD	~	MRH	0.237	0.045	5.255	0	0.148	0.325	0.237	0.279
SSD	~	MWP	0.575	0.044	12.978	0	0.488	0.662	0.575	0.678
SSD	~	Topography	0.032	0.026	1.199	0.231	-0.02	0.083	0.032	0.064
MRH	~	MWP	-0.092	0.069	-1.325	0.185	-0.228	0.044	-0.092	-0.092
MRH	~	Topography	0.143	0.04	3.572	0	0.065	0.222	0.143	0.247
MWP	~	Topography	-0.115	0.04	-2.874	0.004	-0.194	-0.037	-0.115	-0.199
CO2	~~	CO2	0.165	0.017	10	0	0.133	0.197	0.165	0.355
SR	~~	SR	0.998	0.1	10	0	0.802	1.193	0.998	0.982
SSD	~~	SSD	0.372	0.037	10	0	0.299	0.445	0.372	0.52
MRH	~~	MRH	0.917	0.092	10	0	0.737	1.096	0.917	0.921
MWP	~~	MWP	0.956	0.096	10	0	0.768	1.143	0.956	0.96
phy	~~	Topography	2.967	0	NA	NA	2.967	2.967	2.967	1
CO2	r2	CO2	0.645	NA	NA	NA	NA	NA	NA	NA
SR	r2	SR	0.018	NA	NA	NA	NA	NA	NA	NA
SSD	r2	SSD	0.48	NA	NA	NA	NA	NA	NA	NA
MRH	r2	MRH	0.079	NA	NA	NA	NA	NA	NA	NA
MWP	r2	MWP	0.04	NA	NA	NA	NA	NA	NA	NA

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Relative Humidity, Soil Phosphorus, and Stand Structure Diversity Determine Aboveground Biomass along the Elevation Gradient in Various Forest Ecosystems of Pakistan

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Abstract: The direct effects of relative humidity and soil on aboveground biomass (AGB) versus the indirect effects mediated by stand structural diversity remain unclear in forest ecosystems across large-scale elevation gradients. Forest inventory data containing 15,260 individual trees and 104 tree species from 200 forest plots were collected. The result shows that the relative humidity, elevation, and Coefficient of Variation of Diameter at breast height (CVD) significantly influence AGB in the Tropical Thorn Forest (TTF). Regarding elevation, CVD was positive and significant, and relative humidity and SR negatively impacted AGB in sub-tropical broad-leaved forests (STBLF). In moist temperate mixed forests (MTMF), soil phosphorus and CVD have a significant positive impact, while relative humidity, elevation, and SR negatively influence AGB. Elevation and CVD have positive, while SR and soil phosphorus have a negative and insignificant effect on AGB in Dry Temperate Conifer Forests (DTCF). Soil phosphorus and relative humidity positively affected AGB ($\beta = 0.021$), while elevation, CVD, and SR negatively affect AGB in dry temperate, pure pine forests (DTPPF). Relative humidity and soil phosphorus have a positive direct effect on AGB in multi-species forests. The current study suggests that AGB primarily depends on relative humidity, soil phosphorus, and elevation in different forest types.

Keywords: forest inventory; environmental factors; stand structure complexity; regional scale; structural equation modeling

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1. Introduction

The influence of species richness (SR) and stand structure diversity (SSD) on aboveground biomass (AGB) has been widely studied and found to be significant. Species richness and SSD contribute to overall ecosystem productivity and health and directly impact AGB. High species richness and stand structure diversity are important for maintaining long-term ecosystem sustainability and resilience [1,2]. SR is considered a part of stand structure complexity (SSC), but variations in tree diameter and height, combined or alone, are primarily categorized as SSC in the forest ecosystem [3]. The ecological tools for linking the various biotic, i.e., biodiversity, stand structure, and abiotic, i.e., relative humidity and soil factors concerning aboveground biomass, have been comparatively well evaluated [2,4–8]. Direct and indirect effects on AGB, SR, and SSC across regional scale ecological gradients persist less contested in natural forest ecosystems [2,4,5].

Nevertheless, ecological theories and regional-level experimental studies indicate that climatic conditions mainly determine AGB [9–12]. Especially in the natural forest ecosystem,

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Carbon sequestration potential of different forest types in Pakistan and its role in regulating services for public health

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A high amount of CO_2 causes numerous health effects, including headaches, restlessness, difficulty in breathing, increased heart rate, high blood pressure, asphyxia, and dizziness. This issue of increasing atmospheric CO_2 can only be solved *via* above-ground and below-ground carbon sequestration (CS). This study was designed to determine the relationship between CS with the crown area (CA), diameter at breast height (DBH), height (H), species richness (SR), and elevation in different forest types of Pakistan with the following specific objectives: (1) to quantify the direct and indirect relationship of carbon sequestration with CA, DBH, H, and SR in various natural forest types and (2) to evaluate the effect of elevation on the trees functional traits and resultant CS. We used the linear structural equation model (SEM) for each conceptual model. Our results confirmed that the highest CS potential was recorded for dry temperate conifer forests (DTCF) i.e., 52.67%, followed by moist temperate mix forests (MTMF) and sub-tropical broad-leaved forests (STBLF). The SEM further described the carbon sequestration variation, i.e., 57, 32, 19, and 16% under the influence of CA ($\beta = 0.90$ and P-value < 0.001), H ($\beta = 0.13$ and p-value $= 0.05$), DBH ($\beta = 0.07$ and p-value $= 0.005$), and SR ($\beta = -0.55$ and p-value $= 0.001$), respectively. The individual direct effect of SR on carbon sequestration has been negative and significant. At the same time, the separate effect of CA, DBH, and H had a positive and significant effect on carbon sequestration. The remaining 20% of CS variations are indirectly influenced by elevation. This means that elevation affects carbon sequestration indirectly through CA, DBH, H, and SR, i.e., $\beta = 0.133$ and P-value < 0.166, followed by $\beta = 0.531$ and P-value < 0.001, $\beta = 0.007$ and P-value < 0.399, and $\beta = -0.32$ and P-value < 0.001, respectively. It is concluded that abiotic factors mainly determined carbon sequestration in forest ecosystems along with the elevation gradients in Pakistan. Quantifying the role of various forest types in carbon dioxide (CO_2) reduction leads to improved air quality, which positively impacts human health. This is an imperative and novel study that links the dynamics of the biosphere and atmosphere.

KEYWORDS

trees functional traits, carbon sequestration, elevation, structural equation model, regional scale, air quality

Chapter 20

Dryland agroforestry; mitigating role in reducing air pollution and climate change impacts

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Abbreviations

AF Agroforestry
AFs Agroforestry systems
C Carbon
CDM Clean development mechanism
CO_2 Carbon dioxide
CS Carbon sequestration
DAF Dryland agroforestry
GHGs Greenhouse gases
MPTs Multipurpose tree species
OM Organic matter
SCS Soil carbon sequestration
SOC Soil organic carbon

20.1 Introduction

Agroforestry (AF) is widely used in drylands around the globe (Zhaohua et al., 1991). A thorough assessment of AF in dryland reported on the administration and multiple tree species (MPTs) suitable to the semiarid and subhumid regions of the island (Rocheleau et al., 1988). Creating enhanced AF innovations with public partners to maximize environmental and social advantages of AF (Banerjee et al., 2020; Raj et al., 2020; Jhariya et al., 2019a,b; Meena et al., 2022). AF is a prominent aspect of property patterns in Central and Eastern Africa's deserts (Tanzania, Uganda, Ethiopia, and Kenya). Trees are utilized for several functions throughout agricultural areas and cattle pasture regimes (Anwar et al., 2019). Trees on the farm and in the house provide a variety of commercial and domestic uses for both wood and nonwood items (Tessema et al., 2012; Khan et al., 2014; Abbas et al., 2017; Khan et al., 2017; Meena et al., 2022b). Agronomic strategies geared toward olives (*Olea europaea*) and cork oaks (*Quercus suber*) are used in Tunisia, Morocco, and Algeria (Tanasijevic et al., 2014). *Argana spinosa* tree silvopastoral systems, which cover around 800,000 acres in Morocco's semiarid and desert regions, have a long history. Growers favor the farming of saltbush (*Atriplex nummularia*) and barley in the area, where persistent water shortages and frequent droughts are common. Besides increasing soil water conditions, this traditional farming supplies nutritional feed throughout key lean times (Ashkezari et al., 2018). Turkey's alley planting of barley and fodder plants beneath pistachio, olive, and grape trees was discovered (Gundogan et al., 2010). In addition to enhancing fodder and cereal yield, AF protects against soil and nutrient depletion due to sufficient water and enhances nutrient supply (Haj-Amor et al., 2022; Choudhary and Meena, 2022). Israel is famous for its capacity to transform desolate land into fertile farmland, especially via AF. One of the 10 leading approaches to combat degradation in the state is to enhance AF techniques. AF innovations are dependent on an upgraded edition of an age-old culture of rerouting rising

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Assessment of Aboveground Carbon stock in the woody vegetation of the Kirthar Range of Mountain Sindh, Pakistan; a step towards climate change assessment

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Abstract

Woody vegetation plays a significant role in the ecosystem services and functions including carbon stock, climate regulation, pollution control, soil conservation, nutrient cycling and recreation. Therefore, the current study was aimed to document taxonomic diversity, in the Kirthar Range Sindh, Pakistan with special reference to aboveground carbon stock. In this study, the aboveground carbon stock of woody plants was evaluated using quantitative and functional ecological approaches. Forty plots of 20×20 m^2 sizes were established in the region. Diameter at Breast Height (DBH), Height and crown of the tree species were noted for all the individuals having DBH greater than 1 cm. A total of 1328 individuals belonging to 14 different species and 7 plant families were reported. Our findings confirmed the higher aboveground carbon stock potential in the species of Acacia modesta 7064.5 (lbs), followed by Tecomella undulata 10573.3 (lbs) and Prosopis juliflora 1749.9 (lbs) per year. The lower amount of carbon stock potential per year were recorded in the species of Grewia villosa 2.71 (lbs), Grewia tenax 2.28 (lbs), and Maytenus senegalensis 2.39 (lbs). The results prove that the dominant woody vegetation species play leading roles in the aboveground carbon stock of the Kirthar range Sindh, Pakistan. Thorny vegetation of Kirthar range play a vital role in the regulation of temperature and balancing the climate change via carbon sequestration and can further be evaluated for numbers of other aspects as well.

Key words:

Aboveground Carbon stock; Woody vegetation; Kirthar Range; Thorny Vegetation, Climate Change