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Assessment of Carbon Stock Potential in Sub-Tropical Rangeland Ecosystems: A Case Study of Dak Ismail Khel, KP, Pakistan

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Abstract. Rangelands play a vital role in climate change mitigation and adaptation by sequestering carbon when properly managed. However, limited data exist on carbon stocks in Pakistan's rangelands. This study assessed carbon stocks in the rangeland of Dak Ismail Khel, located in the subtropical ecological zone of Nowsehra district, Khyber Pakhtunkhwa. Field data were collected from 39 systematically distributed nested circular plots to estimate carbon in trees, shrubs, and grasses. Seven species were identified, including *Acacia modesta*, *Acacia nilotica*, *Ziziphus nummularia*, *Nerium oleander*, *Capparis aphylla*, *Prosopis juliflora*, and *Desmostachya bipinnata*. Mean above-ground biomass (AGB) was 9.05 $\mathrm{t\,C\,ha^{-1}}$, and below-ground biomass (BGB) was 3.28 $\mathrm{t\,C\,ha^{-1}}$, resulting in a total biomass of 481.6 tons. Mean above-ground carbon (AGC) was 4.25 $\mathrm{t\,C\,ha^{-1}}$, below-ground carbon (BGC) 1.55 $\mathrm{t\,C\,ha^{-1}}$, and total carbon stock 226.2 tons. Soil organic carbon averaged 40.19 $\mathrm{t\,C\,ha^{-1}}$, contributing to a total carbon stock of 1,793.6 tons in the study area. These findings highlight the significant carbon sequestration potential of rangelands and emphasize the need for sustainable management and carbon trading initiatives to enhance climate mitigation benefits.

Keywords: Rangelands, Carbon stocks, Soil organic carbon, climate change, Nowshera.

1. Introduction

Climate change is one of the most pressing challenges of the 21st century (Dalal, 2025). Its primary causes are the excessive emissions of greenhouse gases (GHGs) resulting from the burning of fossil fuels, land clearance, deforestation, and other human-induced activities (Nayak et al., 2020). If GHG emissions continue at the current rate, global mean temperatures could increase by up to 4.8°C by the end of this century compared to pre-industrial levels (Pachauri et al., 2014). Such an unprecedented temperature rise will have severe impacts on Earth's biophysical and socioeconomic systems (Qiu et al., 2024). The Economics of Climate Change argues against the notion that emission reductions are unaffordable, emphasizing instead that the long-term costs of inaction far outweigh the investments needed to mitigate climate impacts (Belrzaeg, 2025). It is now well recognized that climate change is primarily anthropogenic in origin. Human activities have had an indisputable and measurable impact on the global climate system (Salawitch et al., 2017). To address the devastating consequences of global warming, it is therefore essential to explore and implement effective strategies to minimize greenhouse gas emissions and enhance carbon sequestration (Chad, 2023). These strategies directly support Sustainable Development Goal 13 (Climate Action) by promoting measures to combat climate change and its impacts, demonstrating that local interventions, such as carbon stock enhancement in rangelands, contribute to global sustainability targets. Human activities are now recognized as the primary driver of climate change, underscoring the need for coordinated mitigation and adaptation efforts aligned with the SDGs.

Greenhouse gases play a key role in maintaining the Earth's energy balance by trapping heat in the atmosphere (Dilmore & Zhang, 2017), yet their concentrations have risen drastically over the past two centuries due to human activity (Nayak et al., 2020). More than half of the observed increase in global surface temperatures between 1951 and 2010 is attributed to anthropogenic increases in GHG concentrations (Najafi et al., 2015). Carbon dioxide (CO_2), released mainly from fossil fuel combustion and deforestation, is the most significant contributor to this warming (Anwar et al., 2020). Since the pre-industrial era, atmospheric CO_2 levels have risen from approximately 280 ppm in 1800 to about 410 ppm in 2017 (Jain et al., 2020). Between 2000 and 2010, GHG emissions reached an unprecedented level of 53.5 gigatonnes of CO_2 equivalent per year (Edenhofer, 2015). In response, many countries are now obligated to report their GHG inventories to the United Nations Framework Convention on Climate Change (UNFCCC), assessing both their emissions and absorption capacities to guide climate policy and management.

Rangelands play a crucial role in global carbon dynamics as they serve as significant carbon sinks (Derner et al., 2017). Covering approximately 41% of the Earth's terrestrial surface (Reid et al., 2005), rangelands comprise grasses, forbs, shrubs, and trees that provide essential ecosystem services, including wildlife habitat, soil stabilization, and forage for livestock (Mgalula et al., 2021). Depending on climatic conditions, they can be classified into hyper-arid, arid, semi-arid, dry sub-humid, or humid zones, with annual rainfall ranging from less than 200 mm in hyper-arid areas to over 1500 mm in humid regions. These ecosystems support millions of people worldwide by providing livelihoods and contributing to food security and biodiversity conservation (Godde et al., 2020). When properly managed, rangelands have substantial potential for carbon sequestration in both vegetation and soils. Globally, they store between 10% and 30% of the world's soil organic carbon (SOC) and can sequester up to 179 million tonnes of CO_2 annually (McDermot & Elavarthi, 2014). In total, rangelands are estimated to hold nearly 30% of terrestrial carbon stocks, covering about one-third of the Earth's ice-free land surface (Smith, 2002).

Enhancing the carbon storage capacity of these landscapes is a key strategy for mitigating climate change, particularly in regions where emission reductions alone may not suffice. Compared to technological methods such as geological or oceanic sequestration, rangeland carbon sequestration is a more practical, sustainable, and cost-effective solution (Henry et al., 2024). Improving the carbon sink function of rangelands through sustainable land management can therefore significantly aid in reducing atmospheric CO_2 concentrations while maintaining ecosystem health and productivity (McDermot & Elavarthi, 2014). Carbon fluxes in rangeland ecosystems are influenced by various factors, including precipitation, temperature, vegetation composition, and soil characteristics (Yang et al., 2022). These factors interact dynamically and sometimes contradict the assumptions of conventional management practices. As such, land management-based carbon offset projects have gained attention as viable mechanisms to enhance soil carbon storage while generating economic incentives. One such initiative is the Sustainably Managed Rangeland Soil Carbon Sequestration Offset Project introduced by the Chicago Climate Exchange (CCX) in 2009 (Fynn et al., 2009). This program required a minimum fiveyear legal commitment to sustainable grazing management practices, such as rotational grazing, balanced forage utilization, and drought contingency planning.

The goal was to increase soil carbon reserves in designated rangelands while ensuring long-term sustainability. A case study conducted in Wyoming demonstrated that carbon credits could be generated on rangelands at costs ranging from $8 to $17 per metric ton of CO_2 equivalent over 20 years through management interventions such as shrub thinning, alfalfa inter-seeding, and rotational grazing (De Steiguer et al., 2008). Although the carbon market prices on the CCX fluctuated between $1 and $5 per ton of CO_2 equivalent at the time, the study highlighted the competitive potential of rangelands compared to croplands and forests as sources of tradable carbon credits. Pakistan, with a total land area of 87.98 million hectares, is characterized by extensive agricultural, livestock, and forestry sectors (Tahir & Khaliq, 2018). Approximately 60% of this land (52.2 million hectares) comprises rangelands, which provide essential grazing resources for over 100 million livestock during the summer season (Masood, 2003). These rangelands are not only critical for rural livelihoods but also represent a significant opportunity for carbon sequestration, particularly under sustainable management regimes. In the province of Khyber Pakhtunkhwa (KP), rangelands exhibit diverse topography and climatic conditions ranging from high-altitude, snow-covered mountains in the north to arid plains in the south (Nasir et al., 2024). The northern mountainous regions receive over 1500 mm of annual precipitation, including snowfall, whereas the southern plains receive less than 250 mm, often experiencing extreme summer temperatures exceeding 50°C (Zafar et al., 2024).

Consequently, the vegetation composition, productivity, and soil carbon potential vary widely across the region. Estimates of rangeland area in KP also vary among studies. The Forestry Sector Master Plan (1992) reported 4.894 million hectares (48.1% of the total area) (Pakistan, 1992), while the National Forest and Rangeland Resource Assessment Study (2004) (Pakistan, 2004) estimated 4.73 million hectares (46.5%) (Plan, 1988; Reid, 1992). The National Land Use Plan (1999) suggested a smaller area of 3.848 million hectares (27.5%) (Pakistan, 1999), and the Landcover Atlas of Pakistan (2012) reported 1.978 million hectares (26.5%) (Pakistan., 2012), primarily comprising alpine pastures and shrublands. Within the subtropical dry zone, particularly in Peshawar, Nowshera, and Mardan districts, rangelands consist mainly of arid and semi-arid grasslands with low annual rainfall (230–350 mm) and limited soil moisture. Dominant vegetation includes Cymbopogon, Eleusine, Cenchrus, and Saccharum species, with average forage production estimated between 400 and 500 kg/ha.

District Nowshera, located in Khyber Pakhtunkhwa, covers approximately 181,610 hectares and exhibits a mix of forests, agricultural lands, barren areas, water bodies, and settlements. Rangelands occupy around 46,760 hectares, representing 25.8% of the district’s total area (Bukhari et al., 2012). These rangelands are vital for local livelihoods and livestock grazing, yet information on their carbon stock potential remains scarce. The region faces increasing threats from rising temperatures and water scarcity, which accelerate evapotranspiration and reduce soil moisture, leading to vegetation stress and land degradation. Understanding the carbon storage capacity of Nowshera’s rangelands is therefore essential for developing sustainable management strategies that enhance both productivity and carbon sequestration. In this context, the present study was designed to assess carbon stocks within the rangeland ecosystems of District Nowshera, which lies in the subtropical ecological zone of Khyber Pakhtunkhwa, Pakistan.

The present study aims to quantify carbon stocks in sub-tropical rangelands by assessing both above-ground and below-ground components, including vegetation biomass and soil organic carbon. By understanding carbon dynamics in these rangelands, the study seeks to contribute to sustainable land management, climate change mitigation, and ecosystem resilience. The findings will provide baseline data for carbon accounting and help identify opportunities to enhance the role of Pakistan’s rangelands in mitigating climate change through improved management and potential participation in carbon trading initiatives.

2. Material and Method

2.1. Study Area

Nowshera District is located in Khyber Pakhtunkhwa, Pakistan, along the banks of the Kabul River, approximately 43 km east of Peshawar. The study was conducted specifically in Dak Ismail Khel, a Union Council within this district (Figure 1) (Nasir et al., 2022). Positioned on the historic Grand Trunk Road (34.0105°N, 71.9876°E) (Amin et al., 2025), it serves as an important regional hub and ranks as the 78th largest city in Pakistan and the ninth largest in the province. The district is bordered by Peshawar to the west, Mardan to the north, Charsadda to the northwest, Swabi to the northeast, Kohat to the south, Orakzai to the southwest, and Attock to the east, placing it centrally within Khyber Pakhtunkhwa. Nowshera experiences a subtropical climate with hot, dry summers and mild winters. The summer season (May–September) often records temperatures exceeding 40°C, while the monsoon period (July–September) brings moderate rainfall that supports local agriculture. Winters (November–February) are cool, with temperatures ranging from 5°C to 20°C. Annual climatic variation is distinct, with August being the wettest month and November the driest. This climatic setting, coupled with diverse topography and vegetation, provides a suitable environment for assessing rangeland productivity and carbon sequestration potential in the region.

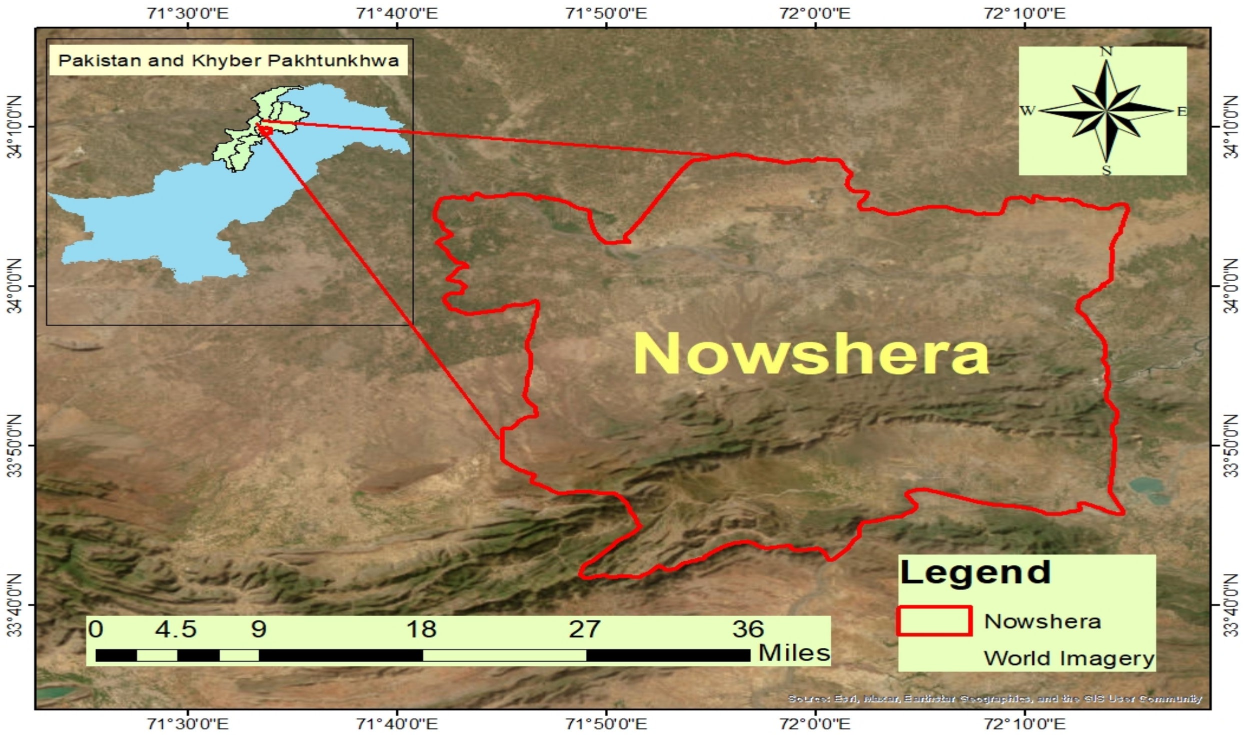

Figure 1. Map of study area

2.2. Methodology

Field data were collected through a comprehensive field survey using the following methodology. The primary species identified in the rangelands of Dak Ismail Khel, a Union Council within Nowshera District, include: *Acacia modesta*, *Acacia nilotica*, and *Ziziphus nummularia*, which are classified as tree species. Additionally, shrub species such as *Nerium oleander, Capparis aphylla*, and *Prosopis juliflora* were observed, while the predominant grass species is *Desmostachya bipinnata*. This includes assessing soil organic carbon content. The current inventory aimed to evaluate the above-ground carbon stocks of these trees, shrubs, and grasses. And Soil Organic Carbon, Primary data was gathered from sample plots established throughout the study area. A total of 39 sample plots were created, with each plot positioned 100 meters apart from the adjacent one, KP, with a focus on tree data, shrubs, grasses, and soil. In order to achieve the research aim, a combination of non-destructive and destructive methods was employed. The non-destructive method was preferred for trees and shrubs due to its minimal impact on the study area and its effectiveness in assessing carbon sequestration. For grasses and soil, a destructive method was applied to accurately measure biomass. This approach involves the collection of data with minimal harm to the sampled vegetation and soil, except for grasses, where direct biomass measurement was necessary. Figure 2 illustrates the flow chart of data collection and analysis.

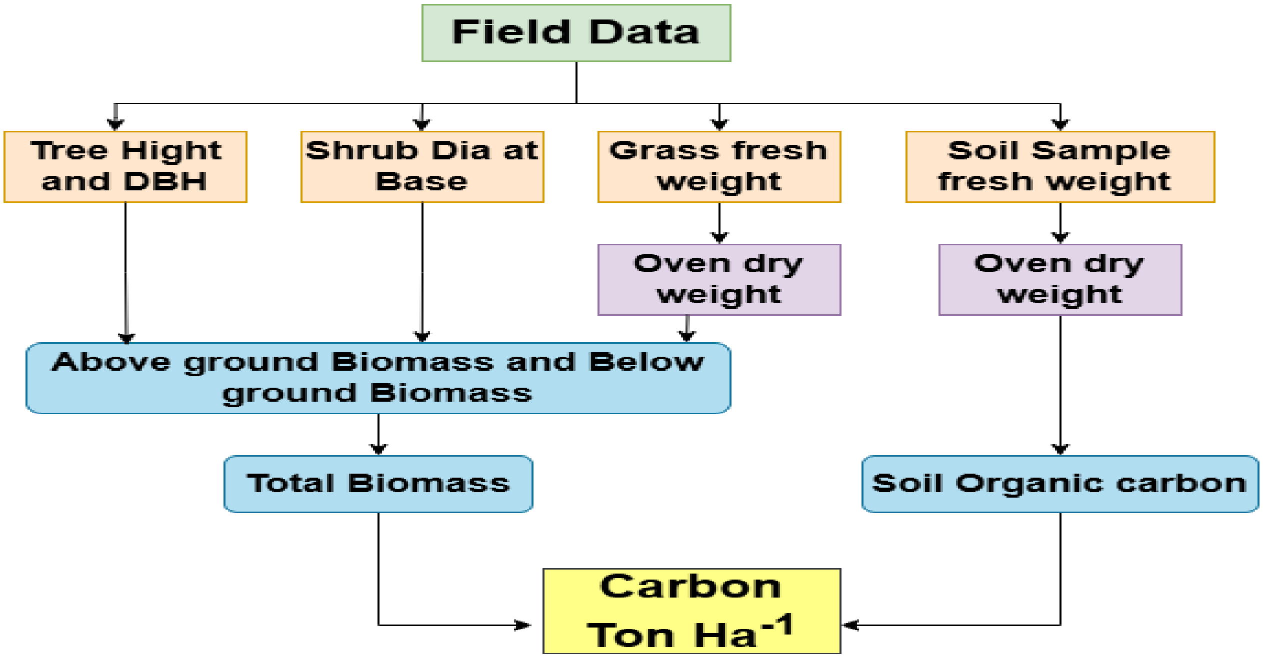

Figure 2. Flow Chart of Data Collection and Analysis

2.3. Sampling Design

Various sampling techniques are utilized to collect data for assessing forest carbon stock, including FAO-like Simple Random Sampling, Systematic Random Sampling, Stratified Sampling, and Cluster Sampling (Kish, 1989). For this research, systematic sampling was selected as the sampling strategy. The study area was divided into a grid pattern of 100m x 100m using Geographic Information System (GIS) software. The intersections of this grid system served as the designated sample plot locations. This strategy was chosen to ensure a representative distribution of sample plots across the study area, thereby minimizing bias, allowing for valid sampling error estimation, and ensuring uniform coverage of the target area. A total of 39 sample plots were delineated within the study area using this grid system, as depicted in Figure 3. These sample plots were laid out on a geo-referenced map of the rangelands in District Nowshera, KPK. The coordinates of the sample plot centers were extracted from the map and input into a GPS device for on-site navigation and data collection. These plots formed the basis for the subsequent data collection process. Before conducting the rangeland inventory, a preliminary analysis of the study area was performed through visual interpretation of Google Earth imagery. There were 4 plots in settlements, 4 in forest land, 2 in agriculture, 2 were completely barren and 28 remaining sample plots were in rangeland areas.

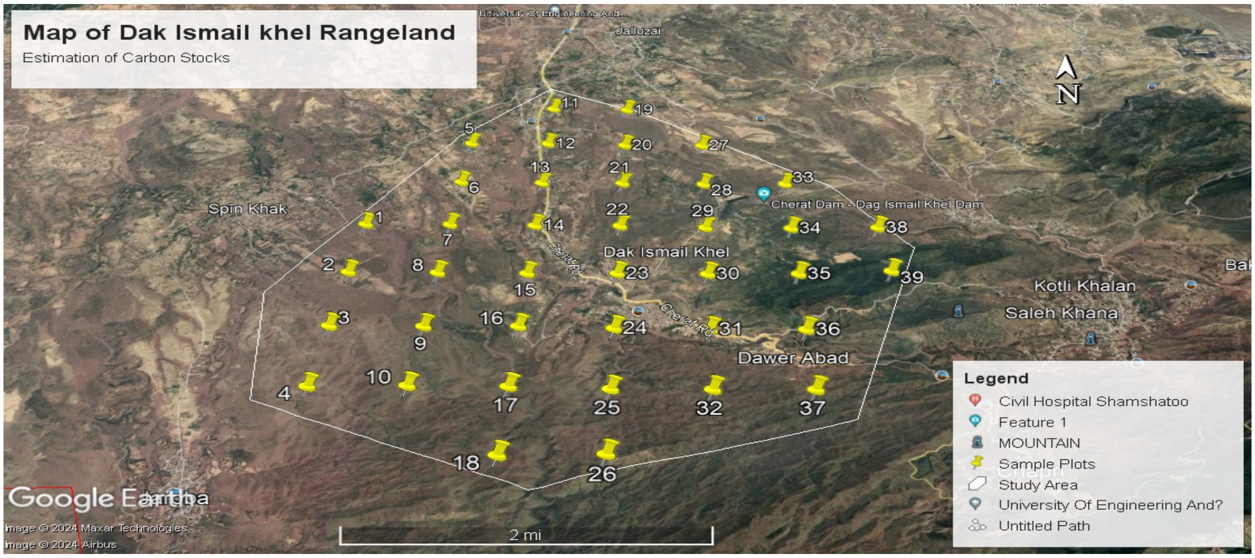

Figure 3. Gridded Map of the Study Area Showing Sample Plots

2.4. Field Measurements

In the current study, biomass and carbon stock were estimated using a nested circular and rectangular plot approach for data collection. Circular plots were chosen for their ease of establishment, particularly in sloping terrains, and to minimize edge effects typically associated with rectangular plots. Rectangular plots were employed for grasses and soil sampling. For tree measurements, circular plots with a radius of 17.84 meters were used. Shrub data were collected within circular plots with a radius of 5.64 meters, as shown in Figure 4. For grasses and soil samples, square plots measuring 1m x 1m were employed. Soil samples were collected randomly at 10 locations from the study area.

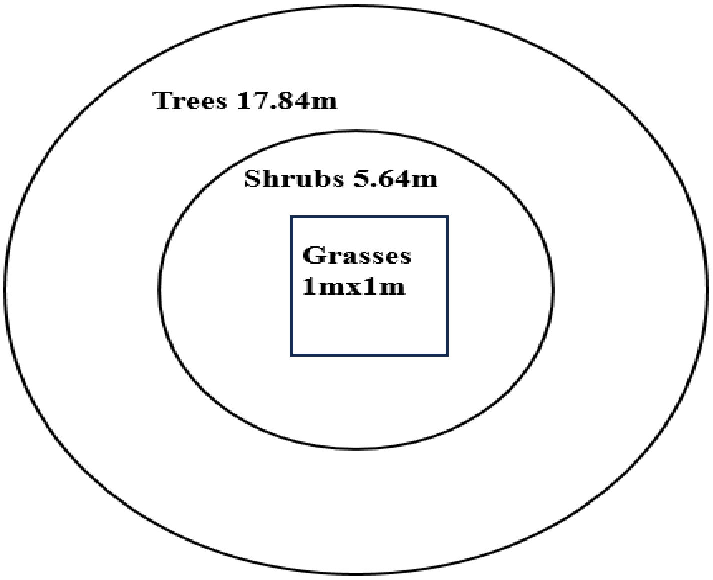

Figure 4. Circular and Rectangular Plot

2.5. Soil samples collection

Soil samples were collected from the top 30 cm layer using a soil auger to measure soil organic carbon (SOC), following the guidelines of the Intergovernmental Panel on Climate Change (IPCC)(IPCC, 2003). The top 30 cm layer was targeted for soil sampling because it contains the majority of soil organic carbon (SOC). Deeper sampling was not feasible due to shallow soils and rocky subsurface conditions. A composite sampling technique was used to estimate soil carbon concentration and bulk density, adhering to established methodology Subedi et al. (2010). In the study area, 10 soil samples were randomly collected from different locations, and their weights were recorded in the field. The samples were then stored in labeled bags and transported to the laboratory for detailed analysis, focusing on the topsoil layer where organic matter is most abundant. In the lab, the samples underwent analysis to determine their Soil Organic Matter (SOM) and Soil Organic Carbon (SOC) content, providing valuable insights into the soil's carbon dynamics.

2.6. Soil Analysis

2.6.1. Soil bulk density

Bulk density refers to the dry weight of a given volume of soil, encompassing both solid particles and pore spaces. This measure is influenced by several factors, including compaction level, particle settlement, and organic matter content. Notably, soils with high organic matter content tend to have lower bulk densities, as the organic material reduces the overall weight of the soil (Morisada et al., 2004). On-site, the soil samples were weighed using a digital balance. They were then sealed in polythene bags and transported to the Pakistan Forest Institute for further processing. At the institute, the samples were air-dried, followed by oven-drying at 105°C for 24 hours. After drying, the samples were re-weighed, and their moisture content (MC%) was calculated using the following equation: Equation (i). This process allowed for the determination of the samples' moisture content (Hartley & Marchant, 1995).

$$Mc(\%) = \frac{Ww - Wd}{Wd} * 10 \text{ ....(i)}$$

The moisture content (MC%) of the soil samples was calculated as the percentage of moisture present. This was done by first recording the initial wet weight (Ww) of the samples. After removing any debris or stones, the net weight was noted. The volume of the soil auger was calculated by measuring its diameter and length, allowing for the determination of bulk density using the formula provided in Equation (ii). The bulk density calculation enabled the assessment of the soil's compactness and porosity (Agus et al., 2010).

$$Bd = \frac{Wd}{Vs} \text{ ....(ii)}$$

where BD is bulk density, Wd oven dry weight of sample (g), and Vs volume of soil core (cm^3).

2.6.2. Soil Organic Matter

Soil organic matter (SOM) was estimated using the loss on ignition (LoI) method, as outlined by (Schumacher, 2002) and (Rahman et al., 2011). The loss on ignition (LoI) method for estimating soil organic matter involves combustion of organic material at high temperatures between 350°C and 440°C, adhering to the protocols established by (Nelson & Sommers, 1996) and (Schumacher, 2002), which enables the quantification of organic matter content through weight loss measurement. A 50g sample of dehydrated soil was placed in a China dish and subjected to high-temperature combustion in a muffle furnace at 400°C for 8 hours, reducing the sample to ash. The resulting ash weight was recorded for each sample, and the organic matter content was calculated using Equation (iii) as described by (Rahman et al., 2011). The soil organic carbon (SOC) content was then determined by applying a conversion factor of 0.58, as recommended by (Rahman et al., 2011), to convert the organic matter content to SOC.

$$OM = Wd - Wa \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(iii)}$$

Where (OM) represents organic matter (g), Wd is the weight of the oven-dried sample (g), and Wa is the weight of the ash (g).

2.6.3. Soil carbon estimation in t C ha⁻¹

Soil carbon stocks (tons/ha) were calculated using the formula: in Equation iv, SOC (%) x Bulk Density (g/cm³) x Horizon Thickness (cm), as described by Pierson et al. (2008). This calculation combines the soil organic carbon percentage, bulk density, and horizon thickness to estimate the total soil carbon content in tons per hectare.

$$\text{SOC (t C ha}^{-1}\text{)} = (\text{SOC content (\%)} \times \text{Soil Bulk Density (SBD) (g/cm}^3\text{)} \times \text{Horizon Thickness (TH) (cm)}) \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(iv)}$$

This formula converts the SOC content from a percentage to a weight per unit area (tons per hectare) by multiplying it by the soil bulk density, horizon thickness, and a conversion factor (100).

2.7. Above-ground Biomass

a) Trees and Shrubs

AGB refers to the total mass of living vegetation above the soil surface, including both woody and herbaceous components. This encompasses stems, stumps, bark, twigs, seeds, and foliage (IPCC, 2006b). Allometric equations applied for the estimation of above-ground biomass (AGB) are presented in Table 1. AGB was calculated in three categories: trees, shrubs, and grasses. For trees, Diameter at Breast Height (DBH) and height were measured using calipers and a Haga Altimeter, respectively. Trees with a DBH greater than 5 cm were classified as trees, while those with a DBH less than 5 cm were classified as shrubs, with diameter measurements taken at the base. AGB for shrubs was calculated using an allometric equation specific to *Dodonaea viscosa*. For major tree species, locally developed allometric equations by PFI were used, while equations from the literature (Chave et al., 2005) were applied to minor tree species.

Table 1. Allometric Equation Used for AGB Calculation

Specie	**Allometric Equation**	**Source**
Acacia modesta	$AGM = 0.2267(D^2H)^{0.8226}$	(Ali et al., 2020)
Acacia nilotica	$AGM = 0.0493(D^2H)^{0.9728}$	(Ali et al., 2020)
Ziziphus nummularia	$AGM = EXP(-9.46108 + 0.52923 * Ln(H) + 2.15113 * Ln(D)) * 0.8 * 1.4 * 1000$	(Ali et al., 2020)
Dodonaea viscosa	$AGM = 0.928(D)^{2.018}$	(Ali et al., 2020)
Others	$AGM = 0.0112(ƒD^2H)^{0.916}$	(Chave et al., 2005)

b) Grasses

Grasses were sampled using a destructive method, where a 1x1 meter frame was laid on the ground, and all living vegetation inside was cut at the base, collected in paper bags, and fresh weight recorded, then labeled and taken to the laboratory for oven-drying at 105°C to a constant weight, with the option to either measure fresh weight in the field and oven-dry in the lab, or collect and dry all samples in the lab of Pakistan Forest Institute (PFI) (Denboba, 2022). Once a sample is dried, calculate the percentage of dry matter using the following formula in Equation v (Denboba, 2022):

$$\% \text{ dry matter} = \left(\frac{\text{Dry Weight}}{\text{Fresh Weight}}\right) * 100 \ldots \ldots \ldots \ldots \ldots \ldots \ldots . (v)$$

where: Dry Weight is the weight of the sample after oven-drying to a constant weight, whereas "Fresh Weight" is the initial weight of the sample, recorded in the field before oven-drying.

2.8. Below-ground Biomass

This pool primarily comprises living roots, excluding fine roots with a diameter less than 2 millimeters. Fine roots of such small diameter are typically omitted due to the challenges associated with separating them from the soil organic matter (IPCC, 2006a). Measuring BGB is often the most challenging aspect of assessing a rangeland ecosystem, typically involving root extraction, weighing, oven-drying, and carbon content estimation. However, due to the difficulty of digging and extracting roots, carbon accounting often relies on regression equations developed from destructive sampling methods, which estimate below-ground carbon content based on ABG, thereby avoiding extensive root excavation (Brown, 2002). The BGB was estimated using a default value from the IPCC Guidelines (2019). To convert biomass to carbon stock, a conversion factor of 0.47, as recommended by the IPCC, was applied to all biomass pools. This means that 47% of the biomass was assumed to be carbon stocks (IPCC, 2019).

2.9. Total carbon stock estimation

The total carbon stock density in the rangeland was calculated by summing the carbon stocks in three main pools: woody vegetation, grasses, and soil. The formula in Equation vi was used:

$$\text{TC (t C ha}^{-1}\text{)} = \text{CWV} + \text{CG} + \text{CS}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{vi}$$

where TC is total carbon in 1 ha of the rangeland, CWV is carbon in the woody vegetation, CG is carbon in the grasses and CS is carbon in the soil pool. While the data collection process encompassed various facets essential to carbon sequestration assessment, certain aspects were intentionally excluded due to practical constraints. Specifically, data collection for leaf litter was not included in this research endeavor.

2.10. General Parameters Recorded

At every sample plot location, the following parameters were assessed or recorded: Date, Plot No, Land use Practices: Forest Land, Agricultural Land, Settlement, Other Land, GPS Coordinates, Evidence of Disturbance, Ground Vegetation Cover and Soil Erosion Status.

2.11. Sample Size

The total area of 39.21 ha of the Dak Ismail Khel range, Nowsehra district, Khyber Pakhtunkhwa. A sampling intensity of 0.1% was employed to gather data from the Rangeland, necessitating the examination of a 3.9-hectare area. To accomplish this, fixed area sample plots measuring 0.1 hectare (1000 square meters) each were employed for data collection. Consequently, a total of 39 sample plots were established within the Dak Ismail Khel range, Nowsehra district, Khyber, for data collection.

2.12. Data Analysis

This section examines the statistical relationships between various vegetation types (trees, shrubs, and grasses) and soil organic carbon (SOC) levels in the rangelands of District

Nowshera, KPK, Pakistan. Using IBM SPSS Statistics 25.0 software, the analysis employs descriptive statistics, correlation analysis, and regression analysis to investigate the impact of different vegetation types on SOC levels, and allometric equations were applied to estimate the biomass of individual trees and shrubs. Grass biomass was calculated from oven-dry weight measurements. Soil organic carbon was estimated based on the organic matter percentage of soil samples collected from the sample plots. The data from the sample plots were then extrapolated to a per-hectare basis and projected for the entire study area.

3. Results

3.1. Frequency of Tree, Shrub and Grass Species

During the field survey, a total of trees from four different species were measured in the rangeland of Dak Ismail Khel, of Nowsehra district, Khyber Pakhtunkhwa. The predominant species were *Acacia modesta*, *Acacia nilotica*, *Ziziphus nummularia*, and *Capparis aphylla*, which constituted 46.15%, 15.38%, 33.33%, and 5.12% of the total tree stock, respectively, as shown in Figure 5. Shrubs consisted of three species: *Prosopis juliflora* (50%), *Nerium oleander* (25%), and *Capparis aphylla* (25%) in Figure 6. The dominant grass species was *Desmostachya bipinnata*. The species composition indicates medium diversity, with six species recorded during the study. The species composition indicates medium diversity, with six species recorded during the study. Observations from the field indicate that the rangeland is subject to anthropogenic pressures, including fuelwood collection and free grazing by livestock. Although these activities suggest potential human impact, further quantitative assessments, such as grazing intensity, vegetation cover change, or soil condition analysis, would be required to formally determine the extent of rangeland degradation and climatic stress.

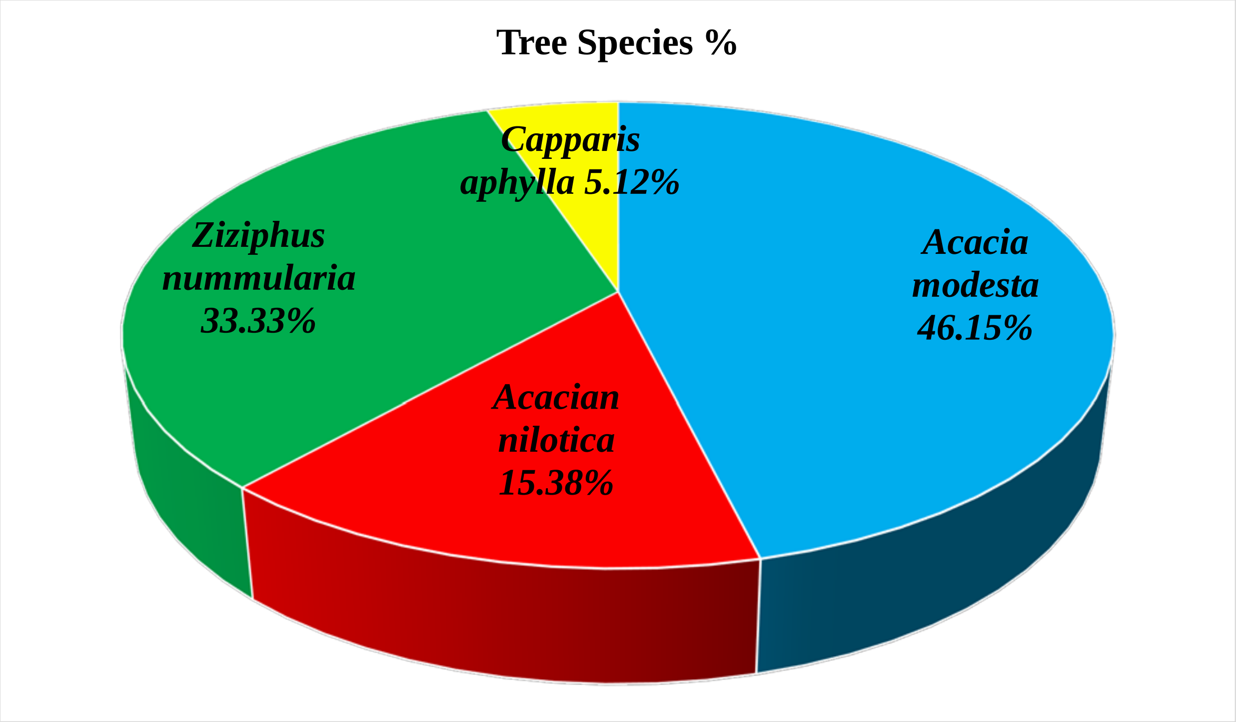

Figure 5. Tree Species Composition of the Rangeland District Nowshera

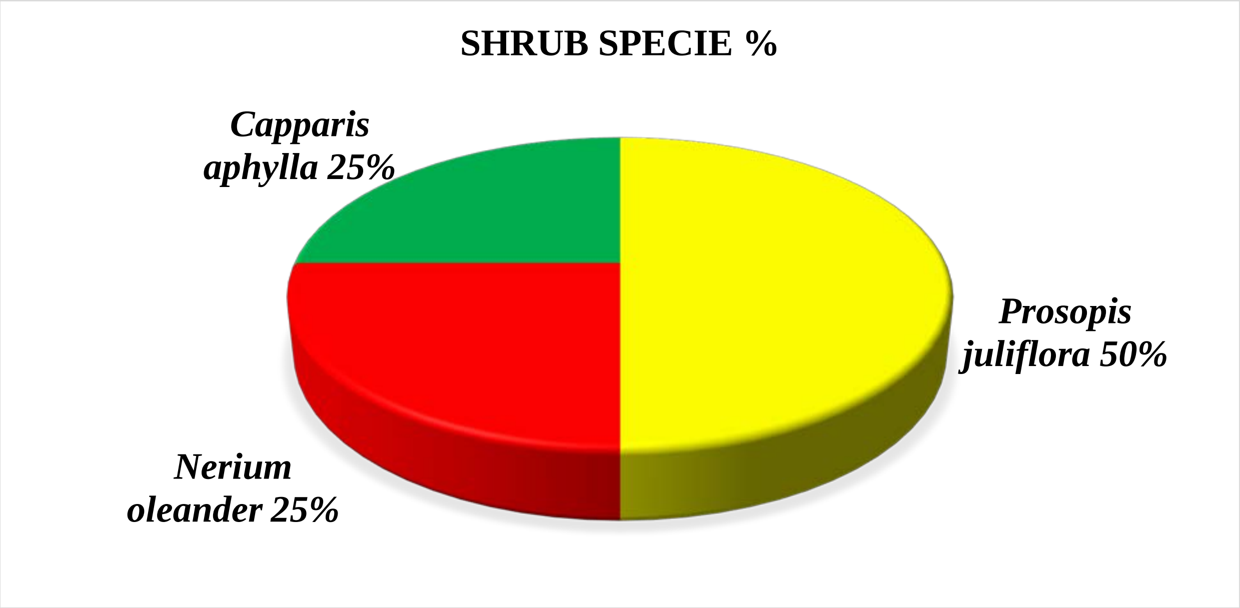

Figure 6. Shrub Species Composition of the Rangeland District Nowshera

3.2. Stand Structure

The results of the study indicated that the trees in the subtropical rangeland of Dak Ismail Khel, Nowshera, Khyber Pakhtunkhwa, have a mean diameter at breast height (DBH) of 35.12 cm and a mean height of 8.73 m, providing a quantitative assessment of tree growth without subjective interpretation. The mean height of these trees was recorded at 8.7meters. In contrast, the shrubs in the same region exhibited a mean diameter at the base of 3.99 cm and an average height of 0.99 meters. These measurements indicate that the shrubs are generally smaller and less mature than the trees, reflecting their role as lower vegetation in the ecosystem. The relatively modest size of the shrubs compared to the trees highlights the structural diversity within the rangeland's vegetation, contributing to a varied and potentially resilient ecological system.

3.3. Statistical Analysis

Statistical analysis of the rangelands of Dak Ismail Khel, Nowshera, Khyber Pakhtunkhwa, revealed that tree and shrub AGM were weakly but significantly positively correlated with soil organic carbon (SOC), whereas grass biomass exhibited a moderate negative correlation, highlighting the differing contributions of vegetation types to soil carbon storage in the study area.

3.3.1. Correlation Analysis

a) Trees and Soil Organic Carbon

The correlation between Trees AGM (kg) and SOC (ton) is positive and significant (r = 0.325, p = 0.046) (Table 2). This suggests that as the AGM of trees increases, the SOC also tends to increase. This relationship indicates that trees play a crucial role in enhancing soil carbon storage.

Table 2. Correlation of Trees and Soil Organic Carbon

Descriptive Statistics			
	Mean	**Std. Deviation**	N
Trees AGM (kg)	725.5357	748.38198	28
SOC_ton	14.3536	21.98429	28
Correlations			
		Trees AGM (kg)	SOC_ton
Trees AGM (kg)	Pearson Correlation	1	0.325^{*}
	Sig. (1-tailed)		0.046
	N	28	28

SOC_ton	Pearson Correlation	0.325*	1
	Sig. (1-tailed)	0.046	
	N	28	28
*. Correlation is significant at the 0.05 level (1-tailed).			

b) Shrubs and Soil Organic Carbon

The correlation between Shrubs AGM (kg) and SOC (ton) is weak but statistically significant (r = 0.323, p = 0.047) (Table 3). This indicates that shrubs contribute to SOC accumulation, although the correlation is slightly weaker than that of trees. It is still significant, highlighting the importance of shrubs in soil carbon dynamics.

Table 3. Correlation of Shrubs and Soil Organic Carbon

Descriptive Statistics			
	Mean	Std. Deviation	N
Shrubs AGM (kg)	2.6379	2.67200	28
SOC_ton	14.3536	21.98429	28

Correlations			
		Shrubs AGM (kg)	SOC ton
Shrubs AGM (kg)	Pearson Correlation	1	0.323*
	Sig. (1-tailed)		0.047
	N	28	28
SOC_ton	Pearson Correlation	0.323*	1
	Sig. (1-tailed)	0.047	
	N	28	28
*. Correlation is significant at the 0.05 level (1-tailed).			

c) Grasses and Soil Organic Carbon

In contrast, the correlation between Grasses BM (t C ha^{-1}) and SOC (t C ha^{-1}) is a moderate negative correlation (r = -0.435, p = 0.021) (Table 4). This suggests that higher biomass of grasses is associated with lower SOC levels. This inverse relationship may be due to the different root structures and organic matter decomposition rates of grasses compared to trees and shrubs.

Table 4. Correlation of Grasses and Soil Organic Carbon

Correlations			
		Grasses BM t C ha^{-1}	**SOC_ t C ha^{-1}**
Grasses BM **t C ha^{-1}**	Pearson Correlation	1	-0.435*
	Sig. (2-tailed)		0.021

	N	28	28
SOC_ **t C ha^{-1}**	Pearson Correlation	-0.435*	1
	Sig. (2-tailed)	0.021	
	N	28	28
*. Correlation is significant at the 0.05 level (2-tailed).			

3.3.2. ANOVA and Regression Analysis

The ANOVA results show that the model, which includes Trees AGM, Shrubs AGM, and Grasses BM, significantly predicts SOC (F = 3.181, p = 0.042) (Table 5). The R² value of 0.285 indicates that approximately 28.5% of the variation in SOC is explained by the model, reflecting the contribution of trees, shrubs, and grasses, while acknowledging that other environmental and ecological factors account for the remaining 71.5% of the variation. The regression coefficients reveal that while Trees AGM and Shrubs AGM have positive but non-significant effects on SOC, Grasses BM has a significant negative effect. This suggests that grasses may reduce SOC more effectively than trees and shrubs increase it.

Table 5. ANOVA and Regression Analysis

<table>
<tr><th colspan="2">Variables Entered/Removed</th><th colspan="6">Model Summary</th></tr>
<tr><td>Variables Entered</td><td>Variables Removed</td><td>R</td><td>R Square</td><td>Adjusted R-Square</td><td colspan="3">Std. Error of the Estimate</td></tr>
<tr><td>Trees AGM</td><td rowspan="6"></td><td>0.533^{a}</td><td>0.285</td><td>0.195</td><td colspan="3">19.72354</td></tr>
<tr><td>Shrubs AGM</td><td colspan="6">ANOVA</td></tr>
<tr><td>Grasses BM</td><td></td><td>SS</td><td>Df</td><td>MS</td><td>F</td><td>Sigma</td></tr>
<tr><td></td><td>Regression</td><td>3712.906</td><td>3</td><td>1237.635</td><td>3.181</td><td>0.042^{b}</td></tr>
<tr><td></td><td>Residual</td><td>9336.436</td><td>24</td><td>389.018</td><td></td><td></td></tr>
<tr><td></td><td>Total</td><td>13049.342</td><td>27</td><td></td><td></td><td></td></tr>
<tr><td colspan="8">Coefficients</td></tr>
<tr><td></td><td colspan="3">Unstandardized Coefficients</td><td colspan="2">Standardized Coefficients</td><td>t</td><td>Sig.</td></tr>
<tr><td></td><td>B</td><td colspan="2">Std. Error</td><td colspan="2"></td><td></td><td></td></tr>
<tr><td>(Constant)</td><td>46.900</td><td colspan="2">18.238</td><td colspan="2"></td><td>2.572</td><td>0.017</td></tr>
<tr><td>Trees AGM (kg)</td><td>0.006</td><td colspan="2">0.007</td><td colspan="2">0.190</td><td>0.761</td><td>0.454</td></tr>
<tr><td>Shrubs AGM (kg)</td><td>1.179</td><td colspan="2">2.058</td><td colspan="2">0.143</td><td>0.573</td><td>0.572</td></tr>
<tr><td>Grasses BM t C ha^{-1}</td><td>-25.747</td><td colspan="2">11.023</td><td colspan="2">-0.406</td><td>-2.336</td><td>0.028</td></tr>
</table>

Y= 0.006xTreesAGM + 1.179xShrubsAGM – 25.747xGrassesBM + 46.900

a. Dependent Variable: SOC_ **t C ha**$^{-1}$

Predictors in the Model: (Constant), Trees AGM, Shrubs AGM, Grasses BM

Enter (Criteria: Probability-of-F-to-enter <= 0.050, Probability-of-F-to-remove >= 0.100).

3.4.Above-ground Biomass

The ABG of trees, shrubs, and grasses, particularly examining their biomass and carbon content. The AGB represents the largest carbon pool within the rangeland ecosystem and is significantly influenced by human activities. Other carbon pools within the ecosystem are directly or indirectly dependent on this biomass. The mean ABG was estimated at 9.05 tons per hectare, with trees contributing 7.26 tons/ha, shrubs 0.25 tons/ha, and grasses 1.54 tons/ha. Figure 7 demonstrates that the total ABG in the rangelands of Dak Ismail Khel, District Nowshera, was estimated at 352.9 tons, with trees contributing 80.00%, shrubs 2.03%, and grasses 17.17%.

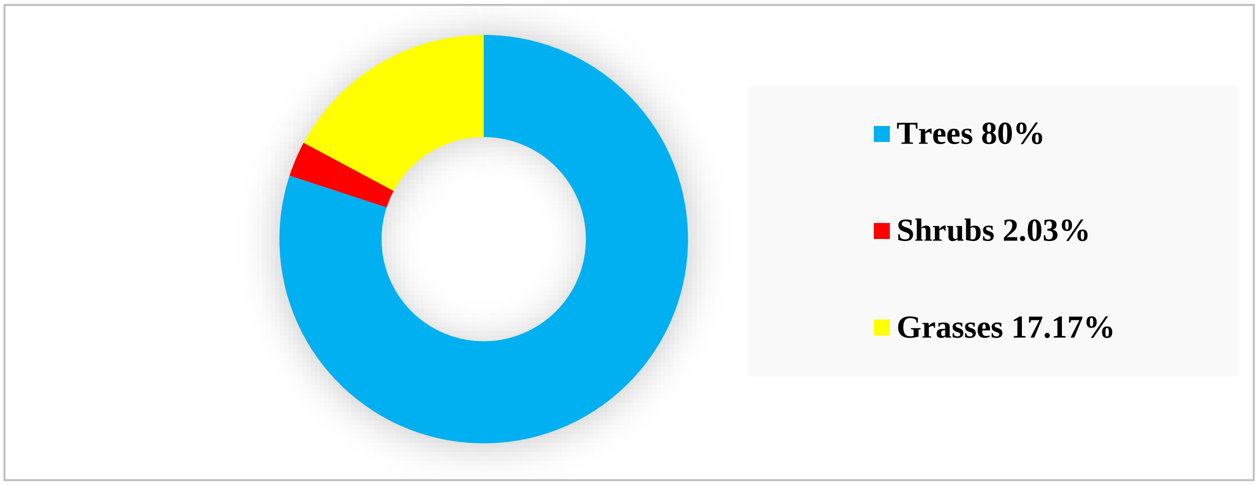

Figure 7. Total Above-ground Biomass

3.4.1. Trees Above-ground Biomass

The results showed that the mean diameter at breast height (DBH) of the trees was 35.12 cm, and the mean height was 8.73 m. The trees in the subtropical rangeland of Dak Ismail Khel, Nowshera, Khyber Pakhtunkhwa, have a total AGB of 283.14 tons, with an average of 7.26 tons per hectare. This biomass accounts for 80% of the total AGB in the region, highlighting the significant role that these trees play in the ecological dynamics of the subtropical rangeland.

3.4.2. Shrubs Above-Ground Biomass

The findings revealed that the average diameter at the base of the shrubs in the subtropical rangeland of Dak Ismail Khel, Nowshera, Khyber Pakhtunkhwa, was 3.99 cm. The shrubs contribute a total AGB of 9.75 tons, averaging 0.25 tons per hectare. This biomass represents 2.79% of the total AGB in the region, underscoring the important ecological role these shrubs play within the subtropical rangeland ecosystem.

3.4.3. Grasses Biomass

The total biomass of grasses in the subtropical rangeland ecosystem of Dak Ismail Khel, District Nowshera, was recorded at 60 tons, making it the second-largest contributor to the overall biomass in the region. This significant biomass contribution underscores the importance of grasses within the rangeland, not only as a key component of the ecosystem's structure but also as a vital source of carbon storage. On average, the grass biomass was estimated at 1.54 tons per hectare, reflecting its widespread presence and ecological significance.

3.4.4. Above-ground Carbon Stock

The table provides data on the above-ground carbon stock for trees, shrubs, and grasses in the rangeland. The average above-ground carbon was calculated to be 4.254 tons/ha, with a total of 165.75 tonnes (Table 6).

Table 6. Above-ground Carbon Stock

Above-ground Carbon Stock			
Species	**Mean AGC t C ha^{-1}**	**Total Above-ground Carbon Stock**	**% of Total Carbon**
Trees	3.41	132.99	80.2%
Shrubs	0.124	4.68	2.8%
Grasses	0.72	28.08	17.0%
Total	4.254	165.75	100%

3.5. Below-ground Biomass

The below-ground biomass, which includes the root biomass of trees and shrubs, was estimated to be 44% of the above-ground biomass according to the IPCC Guidelines for subtropical regions (IPCC, 2019). The mean below-ground biomass was calculated to be 3.28 t C ha^{-1}, resulting in a total below-ground biomass of 128.7 tonnes in the rangelands of Dak Ismail Khel, District Nowshera (Table 7).

Table 7. Below-ground Biomass

Below-ground Biomass		
Species	**Mean BGM t C ha^{-1}**	**Biomass (tons)**
Trees	3.19	124.5
Shrubs	0.11	4.29
Total	3.28	128.7

3.6. Below-ground Carbon Stock

The below-ground carbon stock was calculated from the below-ground biomass using a fraction of 0.47, as recommended by the IPCC (2019). The mean below-ground carbon stock was estimated at 0.775 t C ha^{-1} (Table 8), resulting in a total below-ground carbon stock of 60.45 tonnes.

Table 8. Below-ground Carbon Stock

Below-ground Carbon Stock		
Species	**Mean AGC t C ha^{-1}**	**Total below-ground carbon stock**
Trees	1.50	58.5
Shrubs	0.05	1.95
Total	1.55	60.45

3.7.Total Biomass

The total biomass in the rangelands of Dak Ismail Khel, District Nowshera, was estimated at 481.6 tons, with 73.2% stored in AGM and 26.7% in BGM, emphasizing the dominant contribution of above-ground vegetation to the overall biomass pool.

3.8. The soil bulk density

Which is the mass of dry soil per unit of bulk volume was measured in each study site as part of the present research. The soil particles were analyzed, and the soil bulk density values ranged from 0.834 to 1.580 g/cm^3. The mean soil bulk density across all study sites was calculated to be 1.053 g/cm^3.

3.9. Contribution of Components to Soil Organic Matter

Soil organic matter (SOM) was measured as a percentage in each soil sample plot. The soil samples collected from the rangelands were brought to the laboratory and dried in a combustion machine at 400°C for 8 hours to determine the SOM content. The SOM percentage ranged from 0.80% to 3.70%, with a mean value of 2.29% across all the soil samples analyzed.

3.10. Soil Carbon Stocks

Soil Carbon Stocks were calculated from the soil organic matter percentage using a fraction of 0.58 (Rahman et al., 2011). The mean soil organic carbon was estimated at 40.19 t C ha^{-1}, resulting in a total soil organic carbon of 1567.41 tons.

3.11. Total carbon stock in the Rangeland

The total carbon stock of the trees, shrubs and grasses was 226.2 tons with an average of 5.804 t C ha^{-1}. Out of this, 73.29% was in above-ground biomass, 26.71% in below-ground biomass. The mean soil organic carbon was estimated at 40.19 t C ha^{-1}, resulting in a total soil organic carbon of 1567.41 tons. The carbon stocks in the Rangeland of Dak Ismail Khel District, Nowshera, Khyber Pakhtunkhwa were 1793.61 tons.

4. Discussion

Rangelands are among the most extensive terrestrial ecosystems, playing a crucial role in providing food, fiber, and ecosystem services while contributing significantly to global carbon cycling (Boone et al., 2018; Holechek et al., 2020). The sequestration of atmospheric carbon dioxide into organic carbon forms in soil and vegetation helps improve soil fertility, enhance vegetation productivity, and mitigate climate change impacts (Rodrigues et al., 2023). However, the quantification of carbon sequestration in rangelands is complex due to spatial variability in vegetation composition, soil type, and management practices.

Evaluating carbon fluxes and their controlling factors is therefore essential for understanding the potential of these ecosystems to act as long-term carbon sinks. Several studies have demonstrated that rangeland ecosystems hold substantial carbon reserves, particularly in soils (Henry et al., 2024; Mgalula et al., 2021). Berninger et al. (2015) found that while rangelands generally contain less biomass carbon compared to forests, their soil carbon levels are often comparable or even higher, especially in areas with minimal disturbance.

Abandoned mountain grasslands (areas previously used for grazing or cultivation but left unmanaged for several years) were shown to retain soil carbon levels similar to managed sites, suggesting that soil carbon accumulation may stabilize over time after land-use change. Similarly, Schuman et al. (2002) highlighted that nearly half of the 336 million hectares of grazing lands in the United States are rangelands, storing between 10% and 30% of the world's soil organic carbon. Their research indicated that appropriate grazing management, such as rotational grazing and controlled stocking rates, can increase soil carbon by up to 0.3 Mg C ha^{-1} year^{-1}, with newly established grasslands sequestering as much as 0.6 Mg C ha^{-1} year^{-1}.

In line with these findings, Denboba (2022) examined grazing management practices in the dry lowland rangelands of southern Ethiopia and observed that managed rangelands stored 19.8% more carbon than unmanaged areas. The study reported that herbaceous vegetation contributed 5–15% to total carbon, while woody vegetation contributed only 0.3–1%. More than 90% of the total carbon was stored in soil, underscoring its importance as a major carbon pool. Furthermore, management practices such as enclosures and bush clearing significantly enhanced herbaceous growth and soil carbon sequestration, increasing total carbon storage by 12–26%. Rainfall, altitude, and vegetation type were identified as key factors influencing carbon distribution in these systems.

Conant et al. (2005) also emphasized that improved grassland management practices, including the introduction of legumes, irrigation, and conversion from cultivation, enhance soil organic matter and carbon sequestration, particularly within the first 40 years after implementation. These management interventions can sequester an average of 0.54 Mg C ha^{-1} year^{-1}, depending on biome and climate. Similarly, Ahmad & Nizami (2015) investigated land-use changes in the Kumrat Valley of Khyber Pakhtunkhwa and found that conversion from forest and rangeland to agriculture led to significant reductions in both biomass and soil carbon. Forest soils stored the highest carbon, followed by rangelands, indicating that conserving natural vegetation is essential for maintaining carbon sinks and achieving emission reduction targets under the Kyoto Protocol. Svejcar et al. (2008) and Xiong et al. (2016) also noted that grazing exclusion and reduced disturbance enhance carbon storage in vegetation and soil.

In an Ethiopian pastoral system, Gebremedhn et al. (2022) showed that traditional management strategies such as enclosures increased annual soil carbon stocks by 3%, woody biomass by 11.9%, and herbaceous biomass by 57.6% compared to communal open lands. Their findings highlight that even minor modifications in grazing intensity can lead to substantial improvements in rangeland carbon sequestration potential. The present study’s findings are consistent with these global and regional observations. In the rangelands of District Nowshera, Khyber Pakhtunkhwa, the mean above-ground carbon stock was estimated at 4.254 t C ha^{-1}, with trees contributing 3.14 t C ha^{-1}, grasses 0.72 t C ha^{-1}, and shrubs 0.12 t C ha^{-1}, totaling 165.75 tonnes of above-ground carbon. This value is considerably higher than that reported by Denboba

(2022) for the dry lowland rangelands of Ethiopia, where herbaceous vegetation dominated and woody components were minimal. The relatively high carbon stock in Nowshera's rangelands can be attributed to the greater presence of woody species such as *Acacia modesta*, *Acacia nilotica*, and *Ziziphus nummularia*, which enhance above-ground carbon accumulation. This indicates that the structure and composition of vegetation in Nowshera's rangelands are more similar to savanna-type ecosystems with mixed woody and herbaceous species, leading to improved biomass carbon storage.

The soil bulk density in the rangelands of District Nowshera ranged from 0.834 to 1.580 g/cm³, with a mean of 1.053 g/cm³, which is slightly lower than that reported for the rangelands of Kumrat Dir Kohistan (0.96–1.37 g/cm³; Shah et al. (2015). The relatively lower bulk density in Nowshera may reflect better soil structure, higher organic matter content, and lower compaction due to vegetation cover and root biomass. Bulk density is an important indicator of soil carbon storage capacity; lower values generally correspond to higher porosity and greater organic carbon retention. Variations between the two regions can also be linked to differences in climatic conditions, topography, and management intensity. The mean soil organic carbon (SOC) in the rangelands of Nowshera was 40.19 t C ha⁻¹, with a total of 1,567.41 tonnes. This is slightly below the 42 t C ha⁻¹ recorded in managed Ethiopian rangelands Denboba (2022) but higher than the 32.7 t C ha⁻¹ and 29.8 t C ha⁻¹ reported for rangelands and agricultural lands, respectively, by Ali et al. (2019) in other parts of Khyber Pakhtunkhwa. The relatively high SOC in Nowshera reflects moderate vegetation cover and limited soil disturbance, both of which enhance organic matter accumulation. However, the difference from Ethiopian-managed rangelands may be due to variation in rainfall, soil type, and grazing intensity. These findings underscore the importance of adaptive management strategies to maintain and enhance soil carbon levels under changing climatic conditions. When compared to other land uses, Nowshera's rangelands show an intermediate carbon storage potential. The SOC levels (40.19 t C ha⁻¹) were higher than those of agricultural lands but lower than those of forest soils, which averaged 52.4 t C ha⁻¹ (Ali et al., 2019). This gradient is consistent with global patterns, where forests typically store the most carbon due to dense woody biomass and litter accumulation, followed by rangelands and croplands. The findings emphasize the need for integrated land-use planning that maintains a mosaic of forests and rangelands to optimize carbon sequestration and sustain ecosystem services.

The total carbon stock in the Dak Ismail Khel rangelands of District Nowshera was estimated at 1,793.61 tonnes, comprising 73.29% above-ground biomass and 26.71% below-ground biomass, with a mean SOC of 40.19 t C ha^{-1}. In comparison, Baumber et al. (2020) reported that managed rangelands in southern Ethiopia stored 19.8% more carbon than unmanaged areas, with annual sequestration rates ranging between 1.6–3.5 t CO_2e ha^{-1} for soil and 2.2–5.6 t CO_2e ha^{-1} for total carbon. Here, CO_2e (carbon dioxide equivalent) expresses the greenhouse gas sequestration potential of the rangeland in terms of the equivalent amount of CO_2, allowing comparison of different greenhouse gases on a common scale. The similarity between the trends in Ethiopia and Nowshera highlights the universal role of rangeland management in enhancing carbon storage, regardless of regional differences in vegetation or climate. The findings from the current study further confirm that sustainably managed rangelands in Nowshera have substantial potential for carbon sequestration and climate change mitigation. The high proportion of woody biomass and relatively stable soil organic carbon pool suggest that rangelands, if protected from overgrazing and degradation, can serve as effective carbon sinks. The presence of deep-rooted species like *Acacia modesta* and *Ziziphus nummularia* likely contributes to both above- and below-ground carbon storage. These species not only enhance carbon accumulation but also improve soil stability, reduce erosion, and increase water infiltration, thereby supporting overall ecosystem resilience.

Furthermore, integrating carbon-focused management approaches such as rotational grazing, reseeding native grasses, and establishing grazing enclosures could further increase the carbon sequestration capacity of these landscapes. Similar interventions have proven effective in Ethiopian and Australian rangelands (Baumber et al., 2020; Denboba, 2022), where they enhanced vegetation cover and improved soil carbon retention. In addition, the development of carbon credit initiatives in Nowshera's rangelands could offer financial incentives for local communities to adopt sustainable land management practices, thereby linking conservation with socio-economic development.

Overall, the study provides critical baseline data for carbon stock assessment in subtropical rangelands of Pakistan. It demonstrates that rangelands, though often undervalued compared to forests, hold immense potential for carbon storage when managed sustainably. Continued monitoring and comparative analysis across ecological zones, coupled with community-based management strategies, can further optimize carbon sequestration and contribute to national climate goals under the Paris Agreement.

5. Conclusion and Recommendations

The present study assessed the carbon stock potential of the rangelands in Dak Ismail Khel, Nowshera district, Khyber Pakhtunkhwa, to evaluate their role in soil and vegetation carbon storage, highlighting the contribution of rangeland ecosystems to carbon sequestration at a local scale. The findings revealed that the rangeland ecosystem supports a diverse vegetation structure dominated by tree species such as *Acacia modesta*, *Acacia nilotica*, *Ziziphus nummularia*, and *Capparis aphylla.* The mean diameter at breast height (DBH) and average tree height were 35.12 cm and 8.7 m, respectively, indicating moderately mature stands. The mean above-ground carbon stock was 4.24 $\mathrm{t\,C\,ha^{-1}}$, while the below-ground carbon was 1.55 $\mathrm{t\,C\,ha^{-1}}$, with total above-ground and below-ground biomass estimated at 481.6 tons. Soil organic carbon, a major contributor to total carbon storage, averaged 40.19 $\mathrm{t\,C\,ha^{-1}}$, resulting in a total carbon stock of 1793.36 tons, of which 87.8% was stored in soil and 12.2% in vegetation biomass. The study confirmed positive correlations between tree and shrub biomass with soil organic carbon, emphasizing their significant role in maintaining ecosystem carbon balance. These results underscore the potential of Dak Ismail Khel ranglend, Nowsehra district, Khyber Pakhtunkhwa, as an important carbon sink within the subtropical region of Khyber Pakhtunkhwa. To enhance their carbon sequestration capacity, sustainable management practices such as controlled grazing, reforestation with native species, and soil conservation measures should be adopted. Incorporating these strategies can improve vegetation cover, reduce degradation, and contribute to regional climate mitigation goals while supporting rangeland productivity and ecological resilience.

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