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Functional trait structure in a plant community in Central Anatolian steppe

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Abstract: Exploring the trait structure of grassland plant communities enhances our understanding of how these communities will respond to climate change and disturbances such as herbivory. The trait structure of a plant community was investigated in the Central Anatolian steppe, an ecoregion with high biodiversity that has been largely unexplored in terms of plant functional ecology. Fifty plant species in the community were measured across 9 plant traits, including several leaf traits (leaf area, leaf dry matter content, specific leaf area, leaf thickness, and leaf nitrogen content), two seed traits (seed mass and seed shape), as well as the plant height and stem-specific density. The structure of the plant community was characterized to unveil the functional trait space present. Compared to other grassland communities globally, the plant community in the Central Anatolian steppe exhibited similar functional traits, representing a resource-conservative life history strategy as a whole community. This study represents an initial step towards addressing the significant gap in the literature concerning the Central Anatolian steppes. Further research, including and comparing more steppe habitats in the region, is strongly encouraged.

Key words: Central Anatolian steppe, functional traits, grasslands, growth form, leaf traits

1. Introduction

Functional traits are morphological, physiological, or phenological characteristics that directly or indirectly influence a species' fitness, survival, or reproductive success (McGill et al., 2006; Violle et al., 2007). The functional trait approach enables comparisons among vegetation types or species regardless of their taxonomy, environmental conditions, or growth forms. Functional plant traits can be readily measured at various organizational levels, and these measurements have been standardized through several protocols, such as those proposed by Pérez-Harguindeguy et al. (2013) and Freschet et al. (2021). Due to these advantages, the approach has been widely applied in ecological research to understand species-species, and species-environment interactions, particularly in the face of environmental pressures such as climate change, land use, and grazing (Garnier et al., 2016).

Located at the intersection of the Mediterranean, Caucasian, and Irano-Anatolian hotspots (Mittermeier et al., 2011) and with highly diverse climatic and topographic features, the Anatolian peninsula exhibits an important biodiversity refugium and become a center of diversification (Şekercioğlu et al., 2011). For instance, Anatolia harbors more than 12,000 plant taxa, of which

one-third are endemic (Pils, 2013). The steppe vegetation, which constitutes most of the vegetation, covers 50% of the key biodiversity areas of Anatolia (Eken et al., 2016). The central Anatolian steppes hold a high rate of endemism, 30% of which is found only in that region (Kurt et al. 2006), and recent taxonomic work continues to describe previously unrecognized plant taxa from central Anatolia (e.g., Dönmez et al., 2024). Despite their high-level of biodiversity, the central Anatolian steppes are not well protected, as they are often considered as a secondary vegetation shaped by anthropogenic activities (Şekercioğlu et al., 2011; Ambarlı et al., 2016; Tavşanoğlu and Bernardi, 2024). However, palaeoecological studies have indicated that, through climatic fluctuations and wildfires in the Holocene, central Anatolia was mainly covered by herbaceous and shrubby vegetation (Turner et al., 2008). Nevertheless, increasing human activities and changes in land use have caused habitat fragmentation that limits steppe vegetation in small patches (Kürschner and Parolly, 2012). These fragmentations and continuous disturbances such (land use, climatic changes, etc.) are still threatening the biodiversity of Anatolian steppes (Şekercioğlu et al., 2011; Ambarlı et al., 2016; Ergüner et al., 2019).

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Despite the ecological significance and high biodiversity of the central Anatolian steppes, ecological studies that have used the functional trait approach remain limited. In this regard, characterizing the functional trait structure of the central Anatolian steppes is essential for predicting their future ecological composition under anthropogenic disturbance regimes and climate change. Hence, this study aimed to overcome this deficiency by characterizing the functional structure of the steppe vegetation for the first time in this vegetation type. To achieve this, field and laboratory measurements of several plant traits were taken from samples collected in a representative central Anatolian steppe vegetation community. The results will contribute to a better understanding of the ecological strategies of steppe plants and highlight the value of Anatolian steppes in the context of functional diversity.

2. Material and methods

2.1. Study site

The study site is located east of Ankara, Türkiye (39.950°N, 33.119°E), and supports a well-established steppe plant community on limestone bedrock in central Anatolia (Figure 1). The flora of the site are well-documented, as the result of previous studies conducted in the area (Çetik, 1965; Özüdoğru et al., 2021). The study site is approximately 50 ha in size, surrounded by agricultural fields, and experiences low-intensity grazing.

2.2. Sampling and measurements

2.2.1. Fieldwork

Within the study site, five sampling plots (1 ha each) were selected, and sampling in these plots was conducted between July and August 2020. In total, 50 plant species were sampled to analyze nine different functional traits, including leaf, stem, and seed traits: plant height, stem-specific density, leaf area, leaf dry matter content (LDMC), specific leaf area (SLA), leaf thickness, leaf nitrogen (N) content, seed mass, and seed shape (Table 1). Since they

were relatively easy to measure, 10 individuals per species were sampled for plant height, stem-specific density, and seed traits. Plant height measurements were completed at the study site using a tape meter. For that, 10 individuals of each species were measured. The measured individuals were then sampled for stem-specific density and then transferred to the laboratory at 4 °C in a cooler. Ten leaves from five individuals of each species were sampled for the leaf traits. Care was taken to ensure that the sampled leaves were mature, undamaged, and healthy. For species that produced fewer than 10 leaves, all available leaves that met these criteria were collected. Then, the leaf samples were placed in plastic bags with moistened filter paper and initially stored in a cooler before being transferred to the laboratory, where they were kept at 4 °C until measurement.

Seed and fruit samples were collected at the end of August 2020, when seed maturation was complete. At least 10 fruit samples were collected per individual for seed trait measurements: however, if individuals of a particular species produced fewer fruits, then additional individuals were sampled to reach this number. The collected fruit and seed samples were transferred to the laboratory in paper envelopes for sorting and trait measurements.

2.2.2. Laboratory processes

All measurements of the leaf and stem samples were completed within 24 h of collecting them. Measurements were carried out following the methods of Pérez-Harguindeguy et al. (2013) and Tavşanoğlu and Pausas (2018).

The leaf samples were processed in sequence to obtain the trait measurements. First, the leaf thickness was measured using a digital micrometer. Then, the samples were scanned with a scanner and the leaf areas were calculated from the scanned images using ImageJ (Schneider et al., 2012). After scanning, the leaf samples were waterlogged for 24 h and then weighed using a digital



Figure 1. General appearance of the vegetation in the study area.

Table 1. Traits included in the study and their definitions.

Functional trait	Definition
Growth form	The morphological structure related to the size of a plant.
Plant height	The vertical distance between the ground level and the highest photosynthetic tissue of the plant (Pérez-Harguindeguy et al., 2013).
Stem-specific density	The ratio of the dry mass to the volume of a stem section (excluding the bark in woody species) (Pérez-Harguindeguy et al., 2013).
Leaf area	The one-sided surface area of an individual leaf (Pérez-Harguindeguy et al., 2013).
Leaf thickness	The thickness of the leaf tissue measured between the margin and the midrib (Pérez-Harguindeguy et al., 2013).
LDMC	The ratio of dry mass to water-saturated fresh mass of a leaf (Pérez-Harguindeguy et al., 2013).
SLA	The one-sided area of a fresh leaf divided by its dry mass (Pérez-Harguindeguy et al., 2013).
Leaf N content	The N concentration in leaf tissue expressed as mass of N per unit dry mass (Pérez-Harguindeguy et al., 2013).
Seed mass	The dry mass of a seed (Pérez-Harguindeguy et al., 2013; Tavşanoğlu and Pausas, 2018).
Seed shape	The ratio of the longest to the shortest dimension of a seed (Tavşanoğlu and Pausas, 2018).

SLA: specific leaf area, LDMC: leaf dry matter content.

scale. The samples were then oven-dried at 70 °C for 72 h and weighed to determine the dry mass. The N content of the oven-dried leaves was analyzed using the Kjeldahl method (Tecator, 1987; Kacar, 2009).

To calculate the stem-specific density, the lengths and radii of the samples were measured using a digital caliper. For the radius, three different points were measured and averaged. The approximate stem volume was calculated by multiplying the average radius and length. Then, the samples were oven-dried at 70 °C for 72 h and weighed to determine the dry mass. Following this, the stem-specific density was calculated by dividing the dry mass by the volume.

The seed and fruit samples were sorted using sieves with different pore-sizes. Achene and caryopsis fruit types were accepted as seeds. The seeds were oven-dried at 70 °C for 72 h, and then weighed to determine the dry mass. For the seed shape traits, the seeds were photographed under a stereo microscope, and their widths and lengths were calculated using ImageJ software (Schneider et al., 2012), and then the aspect ratio calculations were performed.

2.3. Species identification and growth form information

Species were identified based on the published books on Turkish flora (Davis, 1965–1985; Davis et al., 1988). When necessary, taxonomic information of the species and families was updated based on global taxonomic datasets, specifically the Taxonomic Name Resolution Service¹ and

¹ Boyle BL, Matasci N, Mozzherin D, Rees T, Barbosa G, et al. (2021). Taxonomic Name Resolution Service (version 5.1). Botanical Information and Ecology Network [online]. Website <https://tnrs.biendata.org/> [accessed 16 April 2025].

² World Flora Online, WFO (2025). World Flora Online [online]. Website <http://www.worldfloraonline.org> [accessed 16 April 2025].

World Flora Online². The growth form of each species was classified as annual herb, biennial herb, perennial herb, suffruticose, subshrub, or shrub, based on the BROT database (Tavşanoğlu and Pausas, 2018) and the published Turkish flora (Davis, 1965–1985; Davis et al., 1988).

2.4. Data analysis

Descriptive analysis was performed to summarize the plant traits of the studied community (minimum, median, mean, and maximum trait values). Additionally, general linear model analysis was conducted to compare the trait values among taxonomic families. For this analysis, the normality of the data was checked using the Shapiro–Wilk test, histograms, and Q–Q plots; and if necessary, a logarithmic transformation was performed to achieve a normal data distribution. Residual plots were also examined after the analyses to evaluate the model assumptions. Post hoc comparisons among groups were conducted using marginal means.

To understand whether the functional traits differed among the different growth forms, a general linear mixed model (LMM) was used, in which the growth form was taken as a fixed effect and taxonomy was taken as a random effect. For each trait, the difference between a null model including only the random effect and a model including the growth form and the random effect was compared using the likelihood ratio test. In doing so, the relationship between the growth form and plant traits was assessed,

accounting for the taxonomy of each species as a random effect.

To further explore the relationships between the traits in the studied plant community, principal component analysis (PCA) was performed on the plant height, seed mass, and SLA, which are representative of the size, reproductive investment, and resource acquisition strategies, respectively, and considered as the main traits representing three dimensions of plant trait schema (Westoby, 1998).

All statistical analyses were performed using R software³.

3. Results

In total, 50 species belonging to 43 genera and 20 families were examined (Table 2). The most common families were Lamiaceae with 10 species, Asteraceae with five species, and Fabaceae with four species. The sample also included six different growth forms: annual herbs (10 species), biennial herbs (two species), perennial herbs (20 species), suffruticose species (five species), subshrubs (nine species), and shrubs (three species).

Plant height, leaf area, leaf thickness, LDMC, and specific leaf area (SLA) were measured for all 50 species. Stem-specific density, leaf N content, seed mass, and seed shape were measured for 45, 26, 42, and 43 species, respectively (Table 3).

The plant height ranged from 10.4 to 181.2 cm, with a mean value of 42.4 cm (Table 3). The shortest species was *Stachys woronowii* (an annual), and the tallest was *Rosa canina* (a shrub). The stem-specific density values ranged from 0.11 to 0.50 cm³/g, with a mean of 0.28 cm³/g. The minimum value was in *Eryngium campestre* (a perennial herb), and the maximum was in *Galium aparine* (an annual).

The leaf area ranged from 4.99 to 11,465.99 mm², with a mean value of 448.75 mm² (Table 3). The smallest leaves were observed in *Galium aparine* (an annual), and the largest were in *Eryngium campestre* (a perennial herb). The leaf thickness ranged from 0.11 to 1.10 mm, with a mean value of 0.31 mm. The thinnest leaves were recorded in *Linaria corifolia* (a perennial herb), and the thickest were in *Verbascum cheiranthoides* (a biennial herb). The LDMC ranged from 134.10 to 908.10 mg/g, with a mean value of 360.40 mg/g. The lowest value was observed in *Verbascum cheiranthoides* (a biennial herb), and the highest was in *Bothriochloa ischaemum* (a perennial herb). SLA varied between 4.47 mm²/mg and 36.69 mm²/mg, with a mean value of 15.02 mm²/mg. The lowest SLA was found in *Stipa ehrenbergiana* (a perennial herb), while the highest was in *Stachys woronowii* (an annual). The leaf N content ranged from 9.50 to 29.00 mg/g, with a mean value of 18.33 mg/g

(measured in 26 species). The minimum value was found in *Verbascum cheiranthoides* (a biennial herb), and the maximum was in *Genista sessilifolia* (a subshrub).

The seed mass ranged from 0.09 to 292.67 mg, with a mean value of 10.70 mg (Table 3). The smallest seeds were recorded in *Thymus sipyleus* (a subshrub) and the largest were in *Amygdalus orientalis* (a shrub). The seed shape, calculated as the ratio of the length to the width, ranged from 1.18 to 7.22, with a mean of 2.08. The roundest seeds were found in *Alyssum murale* (a perennial herb), and the most elongated were in *Stipa ehrenbergiana* (a perennial herb).

The results of the LMM analyses revealed that the plant height, stem-specific density, leaf area, leaf thickness, LDMC, and SLA were significantly affected by the growth form regardless of the taxonomic identity ($p < 0.05$) (Figure 2) (Table 4). In contrast, the leaf N content, seed mass, and seed shape did not show significant variation among the growth forms (Figure 2) (Table 4).

The results of the linear model analysis indicated that the plant height, LDMC, leaf N content, seed mass, and seed shape significantly differed among the families ($p < 0.05$), suggesting a possible phylogenetic signal in these traits (Figure 3) (Table 5). In contrast, the stem-specific density, leaf area, leaf thickness, and SLA did not show significant variation among the families, implying that these traits are less constrained by phylogeny and may be more responsive to environmental or ecological factors (Figure 3) (Table 5).

In the PCA, the first and second components explained 66.4% and 21.7% of the total variance, in total 88.1%. The most variation for the SLA, plant height, and seed mass was observed in the woody plant group, which includes suffruticose, subshrubs and shrubs, and a difference between annual and perennial herbs was revealed by the analysis (Figure 4). Seed mass and plant height were positively associated with Axis 1, while the SLA and seed mass were negatively associated with Axis 2 (Figure 4), indicating a positive relationship between the height and seed mass traits and the negative relationship of the SLA with seed mass and plant height (Figure 4).

4. Discussion

The current analysis revealed the functional trait structure of a central Anatolian steppe plant community. Based on the collected samples, the steppe vegetation can be described as herb-dominated shrubby vegetation with an average plant height of approximately 40 cm. This relatively low plant height suggests that, similar to other temperate grasslands, vegetation in the central Anatolian steppes is strongly influenced by climatic conditions. For instance, in prairies and savannas near tropical zones, increased aridity is associated with shorter plant stature (Allaby, 2006).

³ R Core Team. (2025). R: A language and environment for statistical computing. R Foundation for Statistical Computing. <https://www.R-project.org/>.

Table 2. The studied species and their taxonomic families and growth forms.

Family	Genus	Species	Growth form
Apiaceae	<i>Bupleurum</i>	<i>sulphureum</i>	Annual herb
Apiaceae	<i>Eryngium</i>	<i>campestre</i>	Perennial herb
Apiaceae	<i>Torilis</i>	<i>arvensis</i>	Annual herb
Asteraceae	<i>Anthemis</i>	<i>tinctoria</i>	Perennial herb
Asteraceae	<i>Artemisia</i>	<i>santonicum</i>	Subshrub
Asteraceae	<i>Centaurea</i>	<i>virgata</i>	Suffruticose
Asteraceae	<i>Inula</i>	<i>montbretiana</i>	Perennial herb
Asteraceae	<i>Xeranthemum</i>	<i>annum</i>	Annual herb
Boraginaceae	<i>Lappula</i>	<i>barbarata</i>	Biennial herb
Brassicaceae	<i>Alyssum</i>	<i>sibiricum</i>	Suffruticose
Brassicaceae	<i>Alyssum</i>	<i>murale</i>	Perennial herb
Caprifoliaceae	<i>Scabiosa</i>	<i>argentea</i>	Perennial herb
Caprifoliaceae	<i>Scabiosa</i>	<i>rotata</i>	Annual herb
Caryophyllaceae	<i>Dianthus</i>	<i>micranthus</i>	Perennial herb
Caryophyllaceae	<i>Eremogone</i>	<i>ledebouriana</i>	Perennial herb
Dipsacaceae	<i>Pteroccephalus</i>	<i>plumosus</i>	Annual herb
Euphorbiaceae	<i>Euphorbia</i>	<i>macroclada</i>	Perennial herb
Fabaceae	<i>Astragalus</i>	<i>microcephalus</i>	Subshrub
Fabaceae	<i>Astragalus</i>	<i>micropterus</i>	Subshrub
Fabaceae	<i>Genista</i>	<i>sessilifolia</i>	Subshrub
Fabaceae	<i>Onobrychis</i>	<i>oxyodonta</i> var. <i>armena</i>	Perennial herb
Globulariaceae	<i>Globularia</i>	<i>orientalis</i>	Subshrub
Lamiaceae	<i>Acinos</i>	<i>rotundifolius</i>	Annual herb
Lamiaceae	<i>Marrubium</i>	<i>astracanicum</i>	Perennial herb
Lamiaceae	<i>Phlomis</i>	<i>armeniaca</i>	Perennial herb
Lamiaceae	<i>Phlomis</i>	<i>pungens</i>	Perennial herb
Lamiaceae	<i>Sideritis</i>	<i>galatica</i>	Suffruticose
Lamiaceae	<i>Stachys</i>	<i>cretica</i>	Perennial herb
Lamiaceae	<i>Stachys</i>	<i>woronowii</i>	Annual herb
Lamiaceae	<i>Teucrium</i>	<i>chamaedrys</i>	Suffruticose
Lamiaceae	<i>Teucrium</i>	<i>polium</i>	Perennial herb
Lamiaceae	<i>Thymus</i>	<i>sipyleus</i>	Subshrub
Oleaceae	<i>Jasminum</i>	<i>fruticans</i>	Subshrub
Plantaginaceae	<i>Linaria</i>	<i>corifolia</i>	Perennial herb
Poaceae	<i>Bothriochloa</i>	<i>ischaemum</i>	Perennial herb
Poaceae	<i>Festuca</i>	<i>valesiaca</i>	Perennial herb
Poaceae	<i>Koeleria</i>	<i>crinata</i>	Perennial herb
Poaceae	<i>Pennisetum</i>	<i>orientale</i>	Perennial herb
Poaceae	<i>Stipa</i>	<i>ehrenbergiana</i>	Perennial herb
Polygonaceae	<i>Atraphaxis</i>	<i>billardieri</i>	Subshrub
Ranunculaceae	<i>Consolida</i>	<i>raveyi</i>	Annual herb
Ranunculaceae	<i>Delphinium</i>	<i>venulosum</i>	Annual herb
Ranunculaceae	<i>Nigella</i>	<i>arvensis</i>	Annual herb
Rhamnaceae	<i>Rhamnus</i>	<i>rhodopeus</i>	Shrub
Rosaceae	<i>Amygdalus</i>	<i>orientalis</i>	Shrub
Rosaceae	<i>Rosa</i>	<i>canina</i>	Shrub
Rosaceae	<i>Sanguisorbia</i>	<i>minor</i>	Perennial herb
Rubiaceae	<i>Galium</i>	<i>aparine</i>	Annual herb
Rubiaceae	<i>Galium</i>	<i>verum</i>	Perennial herb
Scrophulariaceae	<i>Verbascum</i>	<i>cheiranthoides</i>	Biennial herb

Table 3. Results of the descriptive analysis. The minimum, median, average, and maximum values obtained for the plant characteristics measured on a species basis. The species with the minimum and maximum values are listed below the respective values. The number of species included in the measurement of each characteristic is provided in the n column.

Trait	n	Min	Med	Mean	Max
Height (cm)	50	10.42	32.73	42.41	181.20
		<i>S. woronowii</i>			<i>R. canina</i>
Stem-specific density (cm ³ /g)	45	0.11	0.27	0.28	0.50
		<i>E. campestre</i>			<i>G. verum</i>
Leaf area (mm ²)	50	4.99	76.15	448.75	11465.99
		<i>G. aparine</i>			<i>E. campestre</i>
Leaf thickness (mm)	50	0.11	0.27	0.31	1.10
		<i>L. corifolia</i>			<i>V. cheiranthoides</i>
LDMC (mg/g)	50	134.10	330.10	360.40	908.10
		<i>V. cheiranthoides</i>			<i>B. ischaemum</i>
SLA (mm ² /mg)	50	4.47	13.32	15.02	36.69
		<i>S. ehrenbergiana</i>			<i>S. woronowii</i>
Leaf N content (mg/g)	26	9.50	17.40	18.33	29.00
		<i>V. cheiranthoides</i>			<i>G. sessifolia</i>
Seed mass (mg)	42	0.09	1.05	10.70	292.67
		<i>T. sipyleus</i>			<i>A. orientalis</i>
Seed shape	43	1.18	1.70	2.08	7.22
		<i>A. murale</i>			<i>S. ehrenbergiana</i>

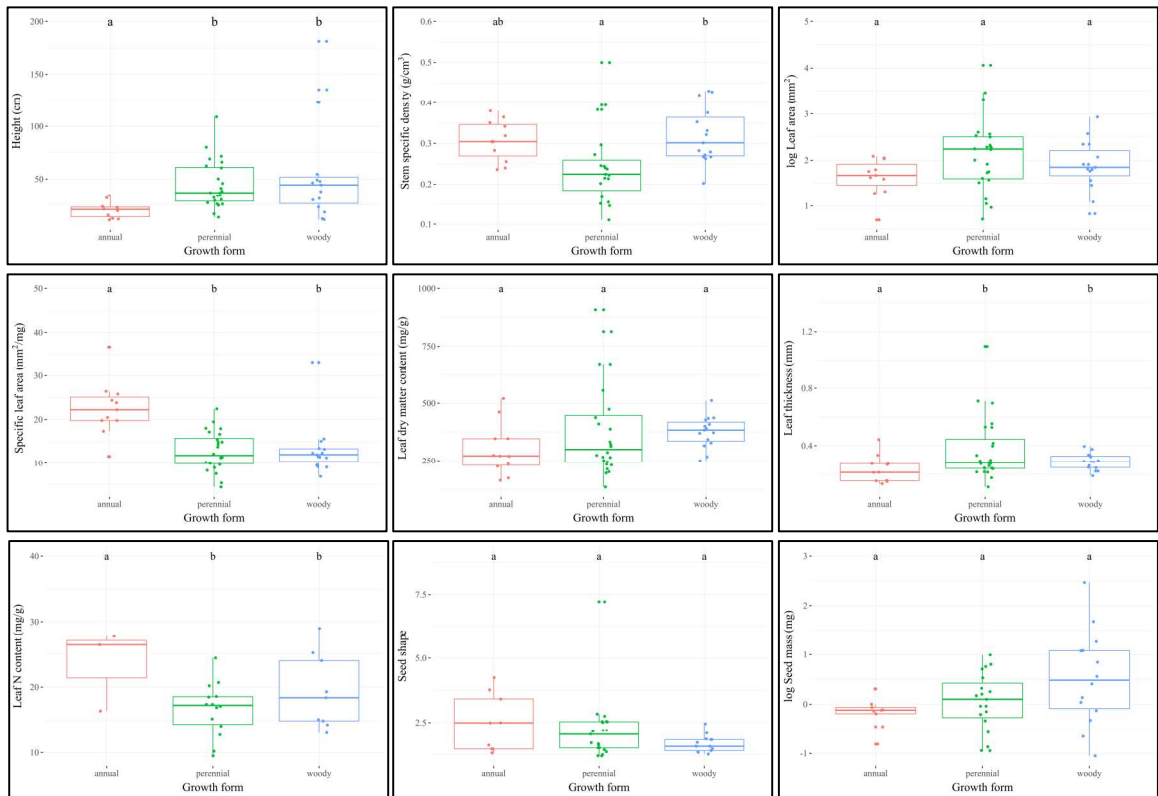


Figure 2. Distribution of traits according to growth forms. Each point on the graph represents a species. In the boxplot graphs, the horizontal line indicates the median, the box extends from the 25th to the 75th percentiles, and the error bars represent 1.5 times the interquartile range. Identical letters on the graph indicate no statistical difference between groups, while different letters indicate a statistically significant difference.

Table 4. Summary of statistical analysis of differences in plant traits among growth forms. The analysis used a LMM. The growth form was taken as a fixed effect, while taxonomy (genus within a family) was considered a random effect. For each trait, the difference between the model including growth form and a null model containing only the random effect was compared using the likelihood ratio test.

Trait	df	logLik	LR	p-value
Height (cm)	6	0.85	14.45	0.0007
Stem-specific density (cm ³ /g)	6	33.8	13.6	0.0011
Leaf area (mm ²)	6	-44.4	6.85	0.0325
Leaf thickness (mm)	6	19	12.45	0.002
LDMC (mg/g)	6	26.8	9.25	0.0098
SLA (mm ² /mg)	6	23.3	20.02	<0.0001
Leaf N content (mg/g)	6	20.5	3.31	0.191
Seed mass (mg)	6	-40.6	3.3	0.1916
Seed shape	6	25.4	3.42	0.1807

LR: likelihood ratio, logLik: log-likelihood, df: degrees of freedom. Statistically significant differences ($p < 0.05$) are highlighted in bold.

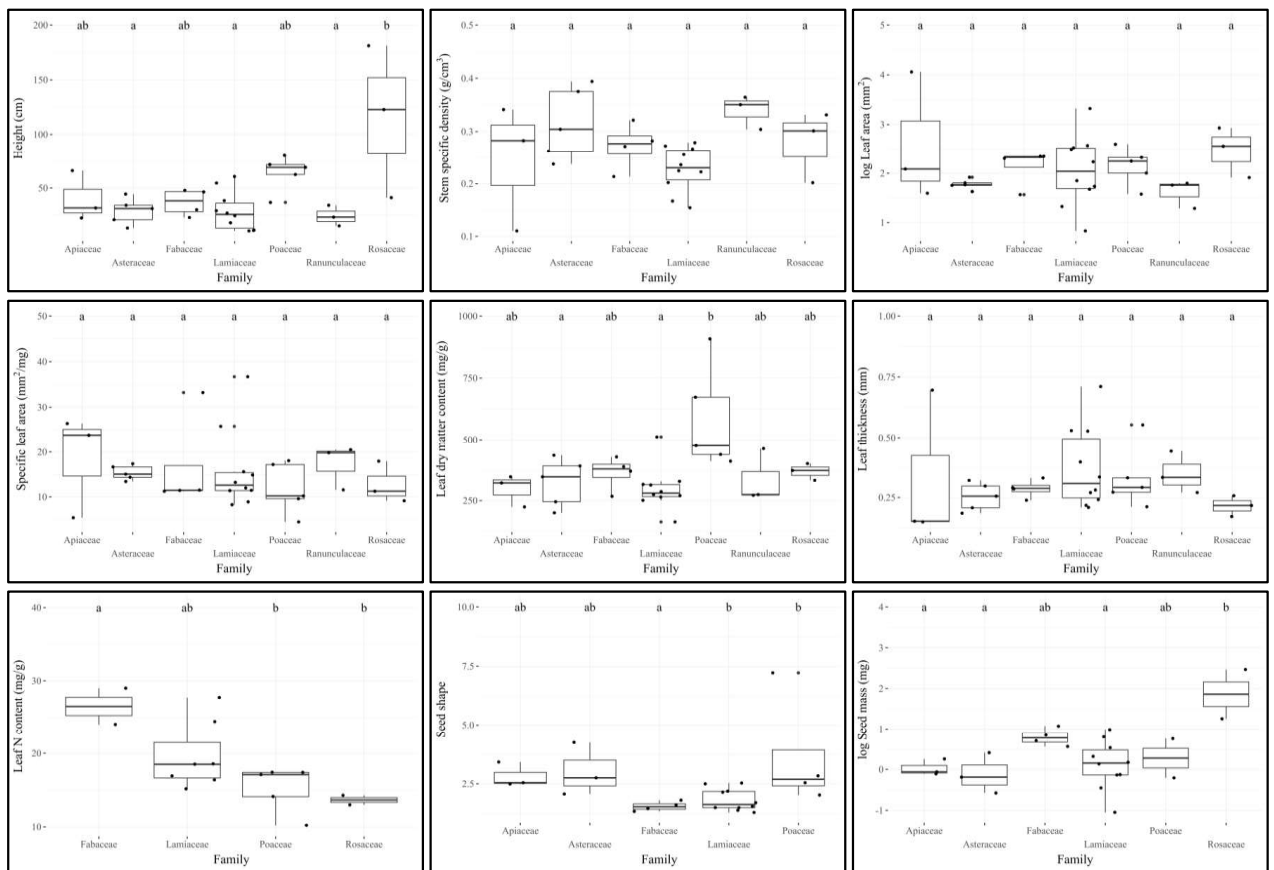


Figure 3. Distribution of traits according to families. Only families with enough species have been considered for comparison. Each point on the graph represents a species. In the boxplot graphs, the horizontal line indicates the median, the box extends from the 25th to the 75th percentiles, and the error bars represent 1.5 times the interquartile range. Identical letters on the graph indicate no statistical difference between groups, while different letters indicate a statistically significant difference.

Table 5. Summary of the statistical analysis of differences in the plant traits among different families. A general linear model was used for the analyses.

Traits	df	SS	F	p-value
Height (cm)	6	1.36	4.13	0.0048
Stem-specific density (cm ³ /g)	5	0.13	1.93	0.1306
Leaf area (mm ²)	6	2.37	1.04	0.4204
Leaf thickness (mm)	6	0.16	0.9	0.5077
LDMC (mg/g)	6	0.3	3.45	0.0122
SLA (mm ² /mg)	6	0.11	0.42	0.8559
Leaf N content (mg/g)	3	0.12	4.92	0.0186
Seed mass (mg)	5	6.88	4.8	0.0058
Seed shape	4	0.36	4.82	0.0074

SS: sum of squares. Statistically significant differences ($p < 0.05$) are highlighted in bold.

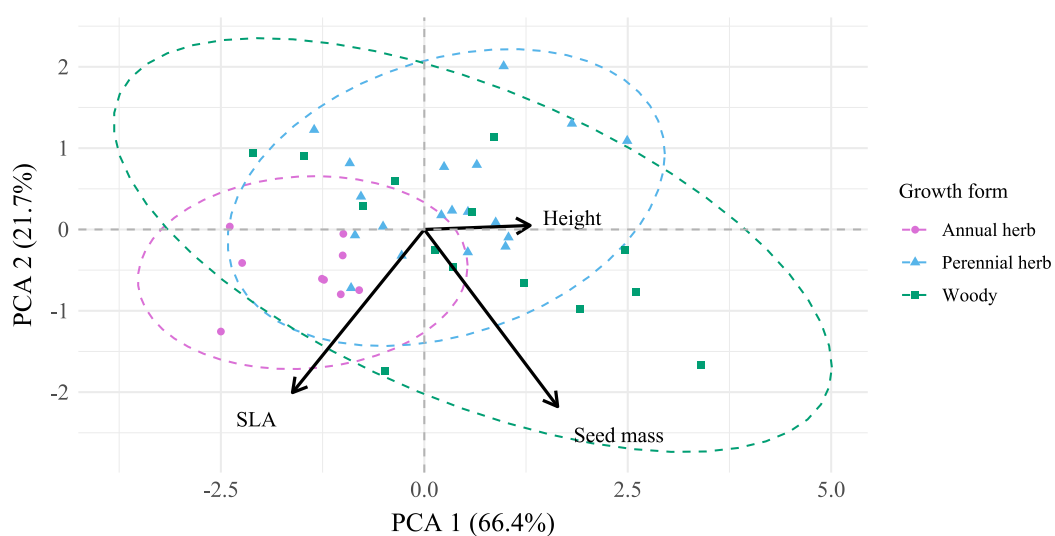


Figure 4. PCA plot of the three main growth forms based on the SLA, seed mass, and plant height of the species. The analysis was performed on a log-scale.

Using the LMM, how the relationship between the growth form and trait structure varies independently of taxonomic effects was examined. Traits such as the height, stem-specific density, leaf area, leaf thickness, LDMC, and SLA, which are associated with the growth form regardless of taxonomy, are directly linked to plant ecological strategies such as resource acquisition, competitive ability, and structural investment. These traits are also known to be related to environmental adaptation and the plant economic spectrum (Wright et al., 2004; Garnier et al., 2016). For instance, taller plants or those with denser

stems may be better adapted to light competition, while variations in the SLA and LDMC often reflect differences in resource-use strategies, with a higher SLA generally associated with fast-growing, resource-acquisitive species. The linear model results, which showed no significant association between the variation in these traits and taxonomy, suggest that they may be shaped predominantly by environmental conditions rather than by evolutionary lineage. In contrast, traits such as the leaf N content and seed traits did not show a significant relationship with the growth form, but their variation was significant at

the family level. This suggests that these traits may be evolutionarily conserved and could carry a phylogenetic signal.

The results of the PCA indicated a clear multivariate structure among the traits, suggesting that certain trait combinations covary across growth forms. The strong explanatory power of the first axis may reflect an ecological tradeoff, for example, between the height and SLA, where taller species tend to have lower SLA values as part of a conservative resource-use strategy. The inclusion of seed mass also allowed for capturing variations in the reproductive strategies, potentially aligned with the leaf economics spectrum.

The findings were broadly consistent with those of previous studies investigating trait variations across temperate and semiarid grasslands. For example, Ladouceur et al. (2019) compared five different temperate grassland types across Europe and demonstrated that growth-related traits such as the plant height and SLA are strongly shaped by environmental gradients. Similarly, Mueller et al. (2024) showed that variation in leaf economic spectrum traits is driven by environmental conditions and disturbance regimes, including precipitation and herbivory. Their study was conducted in a semiarid grassland in Colorado, USA (with annual precipitation ranging from approximately 344 to 394 mm), which closely resembles the climatic conditions of Anatolian grasslands. Consistent with the current results, they found that plant communities in arid environments tend to exhibit a resource-conservative strategy. Furthermore, the present findings align with global patterns reported by Diaz et al. (2016), who identified a positive correlation between plant height and seed mass and a negative correlation between these traits and the SLA. This trait combination reflects a

conservative ecological strategy, favoring persistence and stress tolerance over rapid resource acquisition.

The current study is important in revealing the functional trait structure of central Anatolian steppes and the relationships among these traits. The evaluation of the biodiversity-rich Anatolian steppes through a functional trait approach helps us to better understand the structure and ecological strategies of this vegetation. Understanding plant traits is crucial for predicting how plant species may respond to global environmental drivers, such as climate or land-use change. This study will contribute to a broader understanding of the functional structure of steppes in central Anatolia, and future research in different locations across the region will further enhance our knowledge of steppe ecosystems.

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Author contributions

ÇT conceived the research idea; CÜ, ZLC, BÖ, and ÇT collected the data; CÜ, ZLC, and ÇT performed the statistical analyses; CÜ wrote the first draft; CÜ and ÇT created the final version of the paper. All the authors discussed the results and commented on the manuscript.

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