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Seedling plasticity and phytomass allocation of *Stipa tenacissima* L. populations in arid region of Tunisia

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Abstract

Seedling plasticity in Poaceae, particularly in *Stipa tenacissima* L., represents a key adaptive mechanism for survival in arid steppes. This plasticity is essential for the species' persistence and success under harsh environmental conditions. In the present study, we examined the leaf and root morphological traits and plasticity in relation to the seed-source rainfall of *Stipa tenacissima* (Alfa grass), a key species in the arid and semi-arid environments of the Mediterranean Basin. Populations representing a rainfall range of 100 to 400 mm per year at the seed collection sites were grown in a common garden. Populations differed significantly in TB, leaf traits, and several root traits, with Hassi El Frid showing higher above-ground biomass and leaf architecture, and Sfax populations exhibiting larger root systems. Specific root length (SRL) and leaf traits were positively correlated, while mean root diameter (MRD) decreased with increasing aridity. Plasticity indices revealed high variability among populations, with Sbeitla showing the greatest trait plasticity. Principal component analysis grouped populations according to functional trait expression, explaining 72.7% of total variance. Our results indicate that seedling trait variation is influenced by both local climate and genetic differentiation. Resource allocation patterns support the optimal partitioning theory, with xeric populations favoring root investment and mesic populations favoring leaf development. These findings highlight the adaptive strategies of *S. tenacissima* seedlings to cope with aridity, providing insights for predicting species responses to climate change and informing conservation of Mediterranean drylands.

1. INTRODUCTION

The plasticity of plant morphological traits across habitats has long been of interest to ecologists, as these traits are reliable indicators of plant performance, adaptation, and species distribution patterns (Valladares et al., 2007; Hernández-Calderón et al., 2014). Current research on plasticity is motivated both by the need to predict species' responses to global environmental change (Rehfeldt et al., 2001) and by the recognition that plasticity plays a central role in trait-mediated species interactions (Callaway et al., 2003). Consequently, understanding phenotypic plasticity is essential for forecasting changes in species distributions, community composition, and ecosystem productivity under shifting climate conditions (Lande, 2009).

Stipa tenacissima L. (Alfa grass) forms extensive steppes, covering more than 32,000 km^2 in the western Mediterranean Basin (Cortina et al., 2009). The species typically occurs within the 200–400 mm annual rainfall isohyets (Barber et al., 1997), although it can also be found outside these limits (Le Houérou, 1995). Its broad distribution suggests the ability to withstand diverse climatic conditions through phenotypic plasticity, genetic differentiation, or both (Boussaid et al., 2010). Considerable genetic variability and population divergence have been reported (Boussaid et al., 2010; Krichen et al., 2014, 2017, 2019), while morphological traits linked to aridity tolerance have also been described (Krichen et al., 2024, 2022; Pugnaire et al., 1996). However, the role of phenotypic plasticity in the adaptive capacity of *S. tenacissima* remains largely unexamined.

Seedling establishment is the most vulnerable stage in the life cycle of *S. tenacissima*. At this stage, limited root systems restrict access to deeper soil moisture (Gilbert et al., 2001). Insufficient rainfall increases seedling mortality and hampers natural regeneration of steppes (Poorter, 2005). Seedling size at the beginning of the dry season is therefore a critical determinant of survival under drought. Drought-tolerant species typically adjust biomass allocation to favor acquisition of the most limiting resource (Chambel et al., 2005). In *S. tenacissima*, this pattern is consistent with the "optimal partitioning theory," which predicts preferential biomass allocation to the organs most critical for resource capture under prevailing conditions (Hamdani et al., 2019; Krichen et al., 2019).

Functional root and leaf traits are strong predictors of species' vulnerability and adaptive capacity due to their well-documented physiological basis (Pérez-Harguindeguy et al., 2013). Traits such as high leaf dry matter content (LDMC), reduced specific leaf area (SLA), and narrow or rolled leaves improve drought tolerance by reducing water loss and extending leaf lifespan (Le Houérou, 2001; Liu et al., 2023; Pugnaire et al., 1996; Pugnaire and Haase, 1996). Deep root systems further enhance survival by enabling access to deeper soil water reserves (Puigdefábregas and Mendizabal, 1998). These traits support the persistence of *S. tenacissima* in water-limited environments, while also stabilizing soil and reducing erosion particularly critical in Tunisia's fragile arid ecosystems (Maestre and Cortina, 2004).

Studying functional trait variation in *S. tenacissima* across aridity gradients can provide valuable insights into local adaptation strategies, resilience to climate variability, and biodiversity conservation in drylands. Seedlings exhibit diverse ecophysiological responses, suggesting flexibility in water-use efficiency and stress tolerance that enhances population resilience across environments (Farhat et al., 2024; Hamdani et al., 2019; Krichen et al., 2024, 2014; Zagoub et al., 2022).

To assess phenotypic variation among populations in root and leaf traits, we established a common garden experiment with populations originating from sites along an aridity gradient. We hypothesized that responses to water limitation would differ according to the aridity of the seed source. Specifically, we predicted that seedlings from drier origins would allocate proportionally more biomass to roots, while those from more mesic origins would invest relatively more in leaves under favorable conditions. We also evaluated the degree of trait plasticity across populations to clarify its role in adaptation to environmental variability.

2. MATERIAL AND METHODS

2.1. Plant material

Seeds from five *Stipa tenacissima* populations (Table 1) were collected from different regions along a precipitation gradient ranging from 100 to 400 mm/year, covering semi-arid to arid climates in Tunisia (Emberger, 1954). The experiment was conducted in the garden of the

Table 1. Eco-geographical data of collection sites of five populations of *S. tenacissima*

Site	Latitude	Longitude	Altitude (m)	Mediterranean Bioclimatic Stage	Precipitation (mm)	Temperature (°C)	Annual Mean Rainfall Isohyets (mm/year)
Mahdia	35°19′37.69″N	11°02′05.33″W	6	Lower semi-arid	283	18.6	200–300
Hassi El Frid	35°02′05.21″N	8°54′26.58″W	758	Superior arid	234	17.5	200–400
Sbeitla	35°14′03.82″N	8°57′47.12″W	653	Superior arid	274	17.2	200–400
Thala	35°34′44.54″N	8°40′43.24″W	907	Superior arid	443	15.3	200–400
Sfax	34°41′50.53″N	10°31′30.58″W	393	Lower arid	200	19.0	100–200

Olive Tree Institute (IO), Sfax, Tunisia (34° 44′ 02″ N, 10° 43′ 59″ E). The site has a semi-arid Mediterranean climate with a mean annual temperature of 18.2 ° C and mean annual precipitation of 293 mm. Seeds were sown in January in pots containing a mixture of coco fiber, soil, and peat. The pots were watered daily. Measurements were performed in June, when seedlings had developed sufficient leaf biomass. The De Martonne aridity index (AI) (De Martonne, 1926), calculated as $AI = P / (T + 10)$, where P is annual precipitation (mm) and T is mean annual temperature (°C), was used to characterize the climatic conditions at seed-source sites.

2.2. Experimental measurements

Seven seedlings from each population were analyzed. Seedlings were separated into roots, tillers, and leaves. The number of tillers per seedling (TS) and leaves per tiller (LT) were recorded. Maximum leaf length (LL, cm), as well as leaf and root fresh and dry masses, were measured. Total biomass (TB) was calculated as the sum of leaf and root dry mass.

Leaf traits were measured following Pérez-Harguindeguy et al. (2013). The leaf weight ratio (LWR) was calculated as leaf dry mass divided by total dry mass. Specific leaf area (SLA) was calculated as the one-sided leaf area divided by leaf dry mass. Five leaves per tussock were scanned and analyzed using ImageJ software to determine leaf area. Leaf dry matter content (LDMC) was defined as oven-dry mass divided by saturated fresh mass. Leaf thickness (Lth) was calculated as $Lth = 1 / (LDMC \times SLA)$ following Pérez-Harguindeguy et al. (2013).

Roots were carefully washed, scanned with a flatbed scanner at 800 dpi, and analyzed using GiA Roots software (Georgia Tech Research Corporation and Duke University, 2010–2011). Root/shoot ratio (RS) was calculated as root dry mass divided by shoot dry mass. Mean root diameter (MRD, cm), specific root length (SRL), total root length (RL, cm), and root volume (RV, cm^3) were also measured. Root weight ratio (RWR) was calculated as root dry mass divided by total dry mass. A list of abbreviations is provided in Table 2.

2.3. Plasticity indices and statistical analysis

All statistical analyses were performed using SPSS 22.0 (SPSS Inc., Chicago, Illinois, USA). One-way analysis of variance (ANOVA) with post hoc Student–Newman–Keuls (S-N-K) tests was used to assess differences among populations. The response of *S. tenacissima* traits to the De Martonne aridity index (AI) was also evaluated using ANOVA.

To compare the degree of phenotypic plasticity among populations and traits, the coefficient of variation (CV) was calculated for each variable following Valladares et al. (2006). Relationships among leaf and root traits, as well as between traits and AI, were assessed using Pearson correlation analysis.

Principal component analysis (PCA) was conducted to summarize the multivariate patterns of trait variation and to group populations based on their functional traits, including allocation, architectural, and morphological parameters. Logarithmic transformations were applied to variables when necessary to meet the assumptions of normality and homogeneity of variance prior to statistical analyses.

3. RESULT

3.1. Differences among populations

Seedlings of *Stipa tenacissima* from five populations showed significant variation in biomass allocation and morphological traits

Table 2. Abbreviation used in this article and units applied here.

Abbreviation		Variable	Units
Allocation	**TB**	Total biomass	g
	LWR	Leaf weight ratio	gg^{-1}
	RWR	Root weight ratio	gg^{-1}
Architecture	**TS**	Number tillers per seedling	
	LT	Number of leaves per tiller	
	LL	Maximum leaves length	cm
	RL	Root Length	cm
	RV	Root volume	cm^3
Morphology	**SLA**	Specific leaf area	cm^{2}g^{-1}
	LDMC	Leaf dry-matter content	mg g^{-1}
	Lth	Leaf thickness	mm
	RS	Root : Shoot ratio	
	MRD	Mean root diameter	cm
	SRL	Specific root length	cm g^{-1}

when grown under uniform conditions (Table 3). Total biomass (TB) differed significantly among populations (F = 8.441, P < 0.0001), with Hassi El Frid and Thala populations exhibiting higher TB than Mahdia and Sbeitla. Leaf weight ratio (LWR) and root weight ratio (RWR) also varied among populations (F = 2.634, P = 0.05), indicating differential allocation of resources between above- and below-ground organs.

For architectural traits (TS, LT, LL, RL, RV), no significant differences were observed among populations except for minor variations consistent with allocation patterns. Hassi El Frid population exhibited higher above-ground traits (TS, LT, LL), whereas Sfax and Thala populations showed larger root systems (RL and RV), reflecting adaptation to local aridity conditions.

Morphological traits varied significantly among populations. SLA, LDMC, Lth, RS, and MRD showed significant differences (P < 0.05), while SRL did not vary significantly (F = 1.820, P = 0.140). LDMC and leaf thickness (Lth) were higher in populations from more arid sites (Hassi El Frid, Sfax), while SLA was higher in mesic populations (Sbeitla), consistent with resource acquisition strategies under contrasting environmental conditions.

3.2. Effects of aridity index (AI)

The De Martonne aridity index (AI) showed significant effects on several allocation and morphological traits (Fig. 1, Table 4). TB, RWR, RL, RS, and SRL increased with AI, indicating enhanced root growth and resource acquisition in populations from mesic regions. In contrast, MRD decreased with increasing AI (R^2 = 0.45), reflecting adaptation to arid conditions with

Table 3. Mean (±SE) values for allocation, architecture and morphological traits studied in the different populations.

Variables	Sfax (EL Gonna)	Hassi El Frid	Mahdia	Sbeitla	Thala	F-value	P-value
AI	6.9	8.5	9.9	10.1	17.5		
				Allocation			
TB	0.54 ± 0.012a	0.70 ± 0.09a	0.34 ± 0.03a	0.47 ± 0.08a	0.64 ± 0.21a	8.441	<0.0001
LWR	0.68 ± 0.01a	0.60 ± 0.10ab	0.56 ± 0.07b	0.62 ± 0.08ab	0.56 ± 0.02b	2.634	0.05
RWR	0.32 ± 0.01a	0.40 ± 0.10ab	0.44 ± 0.07b	0.38 ± 0.08ab	0.44 ± 0.02b	2.634	0.05
				Architecture			
TS	6.22 ± 1.02	7.00 ± 1.11	7.50 ± 0.76	6.22 ± 0.91	6.16 ± 0.80	0.447	0.773
LT	3.30 ± 0.22	3.57 ± 0.25	3.03 ± 0.21	3.26 ± 0.15	3.67 ± 0.09	1.60	0.193
LL	12.13 ± 1.05ab	13.43 ± 0.87ab	10.32 ± 0.66ab	13.00 ± 1.31ab	11.54 ± 0.51ab	1.67	0.175
RL	790.81 ± 263.6	641.67 ± 213.89	678.00 ± 226	641.60 ± 213.87	851.22 ± 283.74	1.207	0.320
RV	0.87 ± 0.29	0.66 ± 0.22	0.64 ± 0.21	0.72 ± 0.24	0.77 ± 0.26	0.918	0.461
				Morphology			
SLA	22.40 ± 1.13ab	20.74 ± 0.63a	28.48 ± 1.14bc	33.40 ± 1.05bc	19.67 ± 0.59a	21.301	<0.0001
LDMC	357.43 ± 18.73a	406.48 ± 12.45ab	423.33 ± 5.84b	376.75 ± 5.08ab	412.88 ± 10.62b	3.341	<0.0001
Lth	1.31 ± 0.12a	1.20 ± 0.05a	0.84 ± 0.04b	0.80 ± 0.02b	1.24 ± 0.04a	9.021	<0.0001
RS	0.62 ± 0.11b	0.94 ± 0.14b	1.12 ± 0.20a	0.73 ± 0.10b	1.08 ± 0.09a	2.493	0.05
MRD	0.032 ± 0.001a	0.031 ± 0.001ab	0.029 ± 0.001b	0.032 ± 0.001a	0.029 ± 0.0009b	2.720	0.02
SRL	943.43 ± 314.48	1022.03 ± 340.68	1074.60 ± 358.20	1265.00 ± 421.67	1102.44 ± 367.48	1.820	0.140

Different letters indicate significant differences between populations (post hoc S-N-K test at P<0.05 level). Values are Mean (±SE) of n=7 seedlings per populations. AI: Aridity Index thicker roots in xeric populations. LDMC was positively correlated with AI, highlighting the role of leaf density in water retention under drought stress. AI had no significant correlation with LWR or SLA, suggesting that some leaf traits are less sensitive to long-term climatic variation.

3.3. Relationships among traits

Correlation analysis revealed several notable relationships among traits across populations (Table 4). SLA and SRL were positively correlated (r = 0.726), suggesting coordinated

Table 4. Correlation matrix of r between different tested parameters in different population of *S. tenacissima.*

Variables	AI	SLA	LDMC	Lth	TS	LT	LL	RS	MRD	RL	RV	SRL	TB	LWR	RWR
AI	1														
SLA	-0.114	1													
LDMC	0.382	-0.158	1												
Lth	-0.008	**-0.924***	-0.23	1											
TS	-0.373	0.12	0.649	-0.384	1										
LT	0.332	-0.732	0.103	0.683	-0.467	1									
LL	-0.438	-0.049	-0.466	0.21	-0.392	0.478	1								
RS	0.501	-0.215	**0.986***	-0.164	0.566	0.128	-0.56	1							
MRD	-0.654	-0.533	-0.502	0.706	-0.028	0.081	0.241	-0.505	1						
RL	0.63	-0.61	-0.093	0.661	-0.548	0.42	-0.364	0.065	0.167	1					
RV	0.119	-0.316	-0.762	0.62	-0.804	0.221	0.108	-0.652	0.492	0.714	1				
SRL	0.394	0.726	0.102	-0.748	-0.197	-0.112	0.14	0.071	-0.882	-0.363	-0.338	1			
TB	0.008	-0.745	-0.066	0.752	-0.404	**0.945****	0.659	-0.075	0.338	0.26	0.244	-0.272	1		
LWR	-0.572	0.021	**-0.963****	0.345	-0.49	-0.094	0.493	-0.968	0.701	0.034	0.707	-0.319	0.138	1	
RWR	0.572	-0.021	**0.963****	-0.345	0.49	0.094	-0.493	0.968	-0.701	-0.034	-0.707	0.319	-0.138	-1.000	1

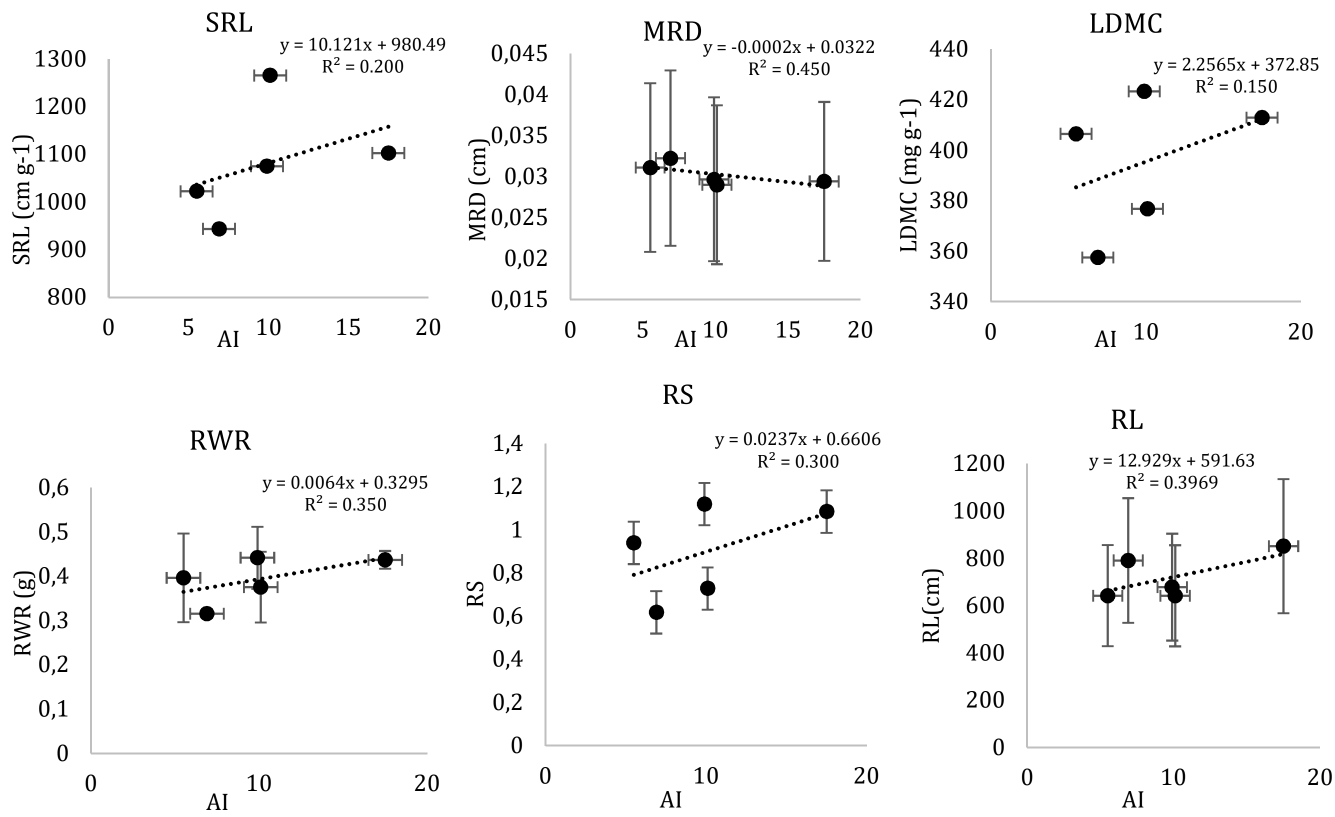

Fig. 1. Responses *S. tenacissima* morphological traits (SRL, MRD, LDMC, RWR, RS and RL) to Aridity Index De martonne (AI). Mean± SE (n=7). See Tables 2 for abbreviations.

strategies for resource capture. LDMC was strongly correlated with RWR (r = 0.963**) and RS (r = 0.986*), indicating that denser leaves are associated with greater root investment. MRD was negatively correlated with SRL (r = -0.882), highlighting a trade-off between fine root length and root thickness. Leaf traits, such as LT, were positively correlated with TB (r = 0.945**), showing that leaf architecture contributes substantially to total plant biomass.

3.4. Plasticity among populations

Plasticity indices (CV) varied among populations for different traits (Table 5). Sbeitla exhibited the highest plasticity in both leaf and root traits, whereas Thala and Hassi El Frid showed lower plasticity. Allocation traits (LWR, RWR) displayed greater variability in xeric populations (Sfax and Hassi El Frid), suggesting adaptive flexibility in response to arid conditions.

3.5. Multivariate analysis

Principal component analysis (PCA) based on functional traits revealed clear segregation among populations (Fig. 2). The first two axes explained 72.67% of total variance (Axis 1 = 45.33%, Axis 2 = 27.34%). Axis 1 was strongly associated with root traits (RV, MRD, RWR, RS) and leaf architecture (TS), while Axis 2 was related to above-ground biomass and leaf morphology (TB, SLA, LT). Populations from mesic environments (Sbeitla) were positioned positively on Axis 2, reflecting high leaf trait plasticity, whereas xeric populations (Thala and Hassi El Frid) exhibited contrasting patterns, consistent with resource allocation strategies under differing climatic pressures.

Table 5. Coefficient of variation over the environments (CV) by Valladares et al. (2006) for *S. tenacissima* phenotypic plasticity in each population.

		Sfax	**Hassi El Frid**	**Mahdia**	**Sbeitla**	**Thala**
Variables	**AI**	6.9	8.5	9.9	10.1	17.5
Allocation	TB	0.22	0.32	0.24	0.72	0.27
	LWR	0.12	0.14	0.11	0.11	0.09
	RWR	0.23	0.21	0.14	0.13	0.11
Architecture	TS	0.41	0.47	0.27	0.44	0.39
	LT	0.17	0.20	0.11	0.25	0.07
	LL	0.30	0.21	0.13	0.24	0.13
	RL	0.31	0.34	0.39	0.35	0.45
	RV	0.27	0.31	0.35	0.34	0.49
Morphology	SLA	0.18	0.12	0.12	0.14	0.15
	LDMC	0.13	0.10	0.04	0.08	0.07
	Lth	0.27	0.18	0.14	0.20	0.14
	RS	0.44	0.36	0.22	0.21	0.22
	MRD	0.07	0.05	0.05	0.04	0.03
	SRL	0.14	0.10	0.10	0.08	0.06

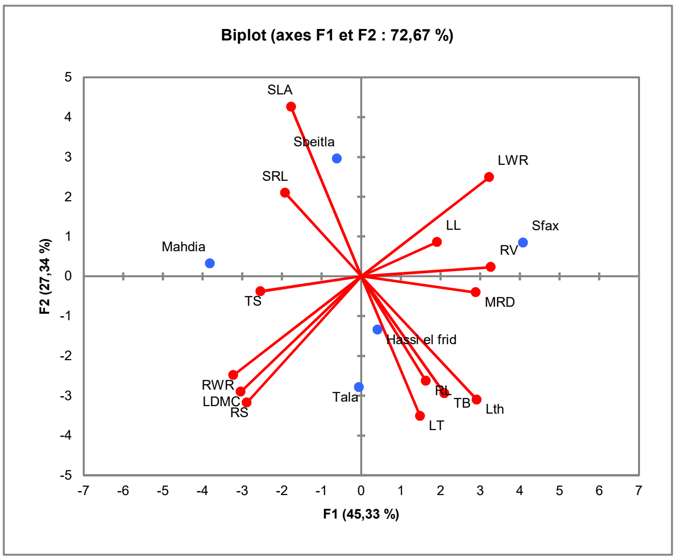

Fig. 2. Distribution of the different allocation, architecture and morphological traits of the *S. tenacissima* populations along the precipitation gradient as a function of principal components 1 and 2 resulting from multivariate analysis among the plant traits included in the study. See Table 2 for abbreviations.

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4. DISCUSSION

In this study, we compared phenotypic plasticity, biomass allocation, and morphological traits of seedlings from five *Stipa tenacissima* populations originating from contrasting environments. Interest in the differences between populations from different seed sources has increased recently (He et al., 2014; Carvajal et al., 2015; Knutzen et al., 2015; Krichen et al., 2014, 2019). However, studies addressing plastic responses in dryland grasses across climatic gradients remain scarce. Our results revealed significant differences in biomass allocation and leaf morphological traits among populations grown under uniform garden conditions. These findings suggest the existence of a clear geographic pattern of genetic variation in *S. tenacissima*, consistent with earlier reports (Boussaid et al., 2010). By contrast, root traits showed little differentiation, except for mean root diameter (MRD).

According to the optimal partitioning theory, plants allocate biomass preferentially to organs capturing the most limiting resource (Bloom et al., 1985). Our results support this framework: populations from drier, hotter sites generally invested more in below-ground structures, while populations from mesic environments displayed stronger above-ground allocation and leaf development. For example, the Hassi El Frid population exhibited high total biomass (TB), tiller number (TS), leaf number (LT), and leaf length (LL), but lower investment in root length (RL) and volume (RV). Conversely, the Sfax population, originating from a more arid region with extended droughts and low precipitation, showed the highest RV, RL, and MRD, combined with thicker leaves (higher Lth) and lower LDMC. These patterns indicate that the Sfax population relies on deeper and thicker root systems, along with leaf traits associated with water-use efficiency, to survive in harsher environments (Hamdani et al., 2019; Krichen et al., 2019). Such differences highlight divergent strategies: mesic populations emphasize rapid above-ground growth, while xeric populations adopt conservative strategies, reinforcing below-ground allocation to cope with limited water.

Differences in biomass allocation likely reflect adaptive differentiation in response to local climatic conditions. Biomass allocation is a critical functional trait influencing plant carbon balance and competitive ability along resource gradients (Evans and Poorter, 2001). In our study, AI was negatively correlated with LWR, LL, and MRD, supporting the idea that *S. tenacissima* modifies leaf morphology and root thickness as adaptive strategies to aridity. Increased MRD in xeric populations may be linked to thicker leaves (positive correlation, r = 0.706), suggesting a coordinated strategy between above- and below-ground traits to enhance drought resistance. Thicker leaves increase water retention and reduce tissue desiccation, contributing to higher leaf weight ratios in arid conditions (Zhu et al., 2023).

Water availability strongly influences biomass partitioning. Djanaguiraman et al. (2018) showed that high temperatures reduce photosynthesis and biomass, and that water deficit amplifies this effect. In our case, populations with higher RWR and RS (notably Thala) allocated proportionally more biomass to roots, consistent with reports that greater root investment enhances drought tolerance by increasing access to deep soil water (Fry et al., 2018; Hanslin et al., 2019; Hilbert and Canadell, 1995). Indeed, higher RWR and RS are widely recognized as key indicators of drought resilience (Deng et al., 2006). However, our results did not show consistent differences among all populations in root-to-shoot ratios, underlining the existence of trade-offs between above- and below-ground efficiency (Feng and Dietze, 2013).

Interestingly, root architecture and morphology showed little correlation with the aridity index, except MRD. This may indicate that root traits are selectively neutral or shaped by non-climatic factors, such as soil texture, nutrient availability, or maternal effects. Similar findings were reported in Eucalyptus sideroxylon, where leaf traits, but not root traits, were linked to rainfall at the seed source (Warren et al., 2005). This reinforces the idea that genotype distribution is influenced by complex ecological filters beyond physiology alone.

Among functional traits, SLA and SRL emerged as key indicators of resource acquisition strategies (Cheng et al., 2015). Both describe the geometry of acquisition surfaces (leaf and root, respectively) and are tightly linked to tissue anatomy and density. In our study, SLA and SRL were positively correlated, consistent with previous observations in grasses (Shipley, 2002; Zhou et al., 2024). High SRL enables fine-root proliferation, increasing access to soil resources, while high SLA supports faster leaf turnover and higher resource uptake capacity (Poorter, 2005). These traits often occur together in “acquisitive” strategies. Moreover, SRL was negatively correlated with MRD, confirming that finer roots are associated with higher resource efficiency, a common pattern in Poaceae (Knutzen et al., 2015). The Sbeitla population was notable for combining high SRL with high MRD, a seemingly paradoxical strategy that could reflect higher root respiration costs but also enhanced plasticity in exploiting different soil layers (Lai et al., 2014).

Leaf traits also varied significantly among populations despite identical growth conditions, demonstrating a strong genetic component. Leaf traits are central to plant strategy syndromes, reflecting trade-offs between growth rate, water conservation, and stress tolerance (Pierce et al., 2013). Our results confirm that *S. tenacissima* populations adopt distinct strategies depending on their ecological origin, ranging from acquisitive (mesic) to conservative (xeric).

Phenotypic plasticity plays a crucial role in shaping these responses. High trait plasticity is often associated with adaptation to variable and unpredictable environments (Gianoli and González-Teuber, 2005; Valladares et al., 2006). In our study, xeric populations such as Sfax and Hassi El Frid displayed higher coefficients of variation in allocation traits (LWR, RWR), suggesting greater capacity to respond flexibly to environmental stress. By contrast, Thala showed low trait plasticity, possibly reflecting a more canalized strategy. PCA further confirmed divergence among populations: Sbeitla, with high root and leaf trait plasticity, contrasted sharply with Thala and Hassi El Frid, underlining population-level differences in adaptive responses.

5. CONCLUSION

Seedling responses of *S. tenacissima* varied significantly among populations, reflecting different strategies of resource allocation between above- and below-ground organs. A positive relationship between these components was observed, suggesting coordinated early developmental patterns that influence resource capture. Root traits appeared largely decoupled from aridity gradients, potentially due to their high plasticity or selective neutrality, while leaf traits showed clearer adaptive differentiation.

Overall, our findings highlight that both genetic variation and phenotypic plasticity shape *S. tenacissima* seedling performance. This dual influence enables populations to persist under contrasting climatic conditions, but also indicates that their responses to climate change will depend on local adaptation histories. Understanding these trait-based strategies is critical for predicting the resilience of Mediterranean dryland ecosystems, where *S. tenacissima* plays a keystone role in soil stabilization and biodiversity maintenance.

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