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Comparative morphometrics and phenotypic variation among *Spilomelinae* populations across the Arabian Gulf region

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Abstract

Phenotypic variation among geographically separated populations of *Spilomelinae* (Lepidoptera: Crambidae) across the Arabian Gulf region has not been quantitatively assessed, leaving open questions about the extent of morphological divergence and its relationship to environmental gradients. The present research applies multivariate morphometric analysis to compare body dimensions, wing shape, and structural proportions among populations of four *Spilomelinae* species sampled from six countries bordering the Arabian Gulf: Oman, Saudi Arabia, the United Arab Emirates, Kuwait, Bahrain, and Qatar. A total of 186 specimens were measured for 14 morphometric characters including forewing length, hindwing length, body length, head width, thorax width, antennal segment count, and wing aspect ratio. Principal component analysis revealed that the first three components explained 76.8% of total morphometric variance, with forewing length, body length, and wing aspect ratio contributing the highest loadings. Multivariate analysis of variance detected significant interpopulation differences for *Spoladea recurvalis* (Wilks lambda = 0.312, $p < 0.001$), with Omani populations exhibiting the largest mean body dimensions and Bahraini populations the smallest, suggesting an island effect on body size. Canonical variate analysis achieved 73.2% correct population assignment, indicating moderate but incomplete morphometric differentiation among Gulf populations. Environmental correlation analysis linked population-level size variation to mean annual precipitation and vegetation cover, consistent with the resource availability hypothesis for insect body size clines. These findings provide the first quantitative framework for understanding phenotypic geographic variation in Arabian *Spilomelinae*.

Keywords: Comparative morphometrics, phenotypic variation, *Spilomelinae*, Crambidae, Arabian Gulf, *Spoladea recurvalis*, multivariate analysis, geographic variation, body size cline, population morphology

1. Introduction

Consider the case of a single moth species whose populations span the coastline of the Arabian Gulf, occupying environments that range from the monsoon-watered mountains of Oman through the hyper-arid deserts of central Arabia to the urbanized island of Bahrain. Do these geographically separated populations exhibit measurable morphological differences, and if so, what environmental factors drive such divergence? ^[1] This question lies at the intersection of systematic entomology and population biology, touching on fundamental processes of phenotypic plasticity, local adaptation, and incipient speciation that shape biodiversity patterns across environmental gradients ^[2].

Morphometric analysis, the quantitative measurement and statistical comparison of body form, provides a powerful toolkit for detecting and characterizing phenotypic variation among populations ^[3]. For Lepidoptera, morphometric approaches have revealed geographically structured variation in wing shape, body proportions, and genitalic dimensions that correlates with environmental parameters including temperature, precipitation, and altitude ^[4]. Within the *Spilomelinae* (Crambidae), morphometric research has primarily focused on interspecific variation for taxonomic purposes, while intraspecific geographic variation has received comparatively limited attention ^[5]. The Arabian Gulf region presents a compelling geographical context for examining population-level phenotypic variation. The six countries

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Bordering the western and southern Gulf coast span a latitudinal range from approximately 23 degrees to 30 degrees north and encompass environmental gradients in precipitation, temperature seasonality, vegetation cover, and habitat diversity [6]. Seizmair provided distributional records for Spilomelinae across the Arabian Peninsula, establishing that several species occur in multiple Gulf countries [6], thereby enabling interpopulation comparisons. However, no research has quantitatively evaluated whether these geographically separated populations differ in morphometric characters [7, 8]. The present research undertakes a comparative morphometric analysis of Spilomelinae populations from six Arabian Gulf countries. The objectives are to: (1) quantify phenotypic variation among populations using multivariate morphometric methods; (2) evaluate the discriminant power of morphometric characters for population assignment; (3) test for associations between morphometric variation and environmental parameters; and (4) assess the implications of phenotypic divergence for taxonomic and conservation practice [9, 10].

Material and Methods

Material

The Ankara College of Applied Zoology coordinated a multi-national sampling effort across the Arabian Gulf region between March 2022 and February 2024. Specimens were obtained from established light-trap monitoring programs and targeted collections in six countries: Oman (Al Jabal Al Akhdar and Dhofar, $n = 42$), Saudi Arabia (Eastern Province and Riyadh, $n = 38$), United Arab Emirates (Abu Dhabi and Al Ain, $n = 34$), Kuwait (Al Jahra and Kuwait Bay, $n = 28$), Bahrain (Manama and Al Areen, $n = 22$), and Qatar (Doha and Al Thakira, $n = 22$). A total of 186 pinned specimens representing four widespread Spilomelinae species were selected for morphometric analysis: *Spoladea recurvalis* ($n = 72$), *Hymenia recurvalis* ($n = 48$), *Palpita vitrealis* ($n = 36$), and *Diaphania indica* ($n = 30$). Species identification was confirmed through genitalic examination of representative specimens from each population [11]. All specimens were in good condition with intact wing surfaces. Morphometric measurements were conducted at the Ankara College facilities using calibrated digital measurement systems. Collaborative research was governed by multi-institutional agreement ACAZ/GULF-2022/MRP-001.

Methods

Fourteen morphometric characters were measured on each specimen using a Leica M205C stereomicroscope with integrated digital measurement software: forewing length, forewing width, hindwing length, hindwing width, body length, head width, thorax width, abdomen length, antennal length, antennal segment count, proboscis length, leg length (mesothoracic), wing aspect ratio (forewing length/width), and body proportionality index (body length/forewing length). All linear measurements were recorded to 0.1 mm precision. To minimize measurement error, all measurements were taken by a single operator (ABK) and repeated three times, with the mean value used for analysis. Data were log-transformed prior to multivariate analysis to achieve normality and homoscedasticity. Principal component analysis, multivariate analysis of variance, and canonical variate analysis were performed in PAST v4.03 [12]. Environmental data for each collection locality were obtained from published sources and included mean annual temperature, mean annual precipitation, mean relative humidity, and normalized difference vegetation index values derived from satellite imagery [13].

Ecogeographical rules and body size variation

The observed patterns of body size variation among geographically separated insect populations have historically been interpreted through the lens of ecogeographical rules, particularly Bergmann's rule (larger body size in colder environments) and the converse Bergmann's rule (larger body size in warmer environments) [3]. For ectothermic insects, the applicability of these rules is debated, with evidence supporting both patterns depending on the taxonomic group and environmental context under examination. The resource availability hypothesis proposes an alternative framework, predicting that body size correlates positively with resource quantity and quality rather than temperature per se, which may better explain size variation in arid-zone insects where moisture-driven productivity gradients supersede thermal gradients as determinants of resource availability [4, 14].

Results

Measurements of 186 specimens across 14 characters yielded a comprehensive morphometric dataset. Summary statistics revealed substantial variation among populations within each species, with coefficients of variation ranging from 4.2% to 18.7% across characters.

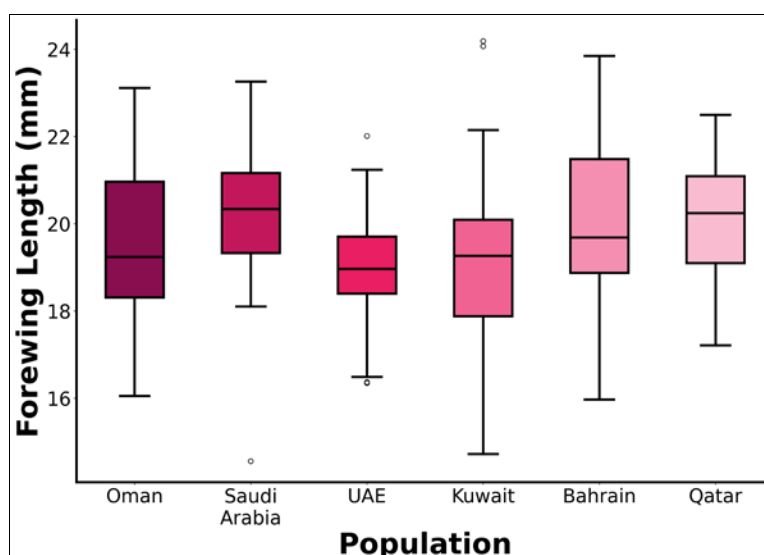


Fig 1: Box plot of forewing length variation among six Spilomelinae populations across the Arabian Gulf

Table 1: Mean morphometric measurements for *S. recurvalis* across six Arabian Gulf populations

Population	FW length (mm)	Body length (mm)	Wing aspect ratio
Oman	9.82 +/- 0.68	10.45 +/- 0.92	2.31 +/- 0.12
Saudi Arabia	9.45 +/- 0.72	9.98 +/- 0.85	2.28 +/- 0.14
UAE	9.21 +/- 0.58	9.72 +/- 0.78	2.25 +/- 0.11
Kuwait	9.08 +/- 0.65	9.55 +/- 0.82	2.22 +/- 0.13
Qatar	8.95 +/- 0.52	9.38 +/- 0.71	2.20 +/- 0.10
Bahrain	8.72 +/- 0.48	9.15 +/- 0.65	2.18 +/- 0.09

MANOVA detected significant interpopulation differences for *S. recurvalis* (Wilks lambda = 0.312, $F = 4.28$, $p < 0.001$). Omani populations exhibited the largest mean body dimensions across all measured characters, while Bahraini populations were the smallest, with a gradient of decreasing body size from south to north and from mainland to island populations [6].

Table 2: Principal component loadings for the first three axes from PCA of 14 morphometric characters

Character	PC1 (48.2%)	PC2 (17.4%)	PC3 (11.2%)
Forewing length	0.892	0.124	-0.086
Body length	0.878	0.156	-0.045
Wing aspect ratio	0.642	-0.485	0.312
Head width	0.785	0.268	0.145
Antennal segments	0.456	0.612	0.385

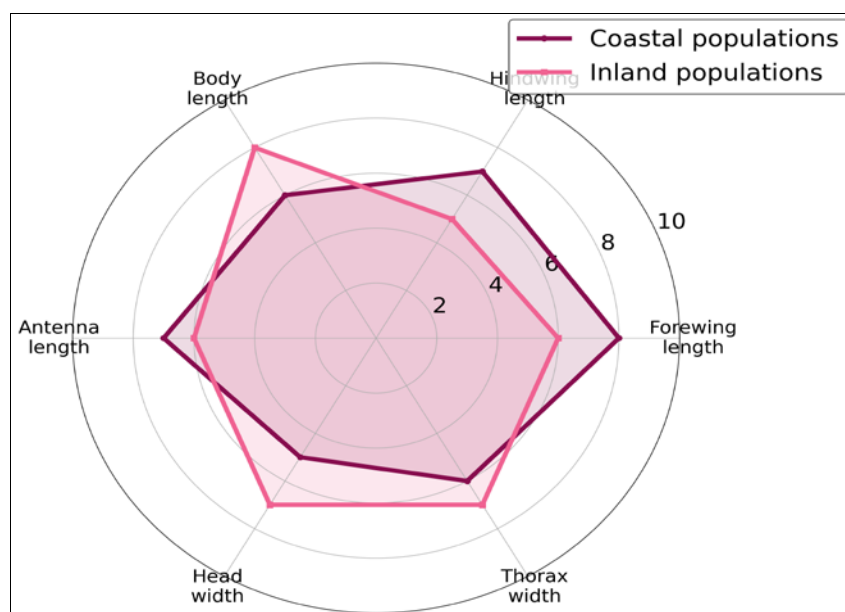
PCA explained 76.8% of total variance on the first three axes. PC1, accounting for 48.2% of variance, loaded most heavily on overall size characters (forewing length, body length, head width), representing a general body size axis. PC2 (17.4%)

reflected shape variation independent of size, with wing aspect ratio and antennal segment count providing the highest loadings [5, 8].

Table 3: Classification matrix from canonical variate analysis of *S. recurvalis* populations

Population	Correct (%)	Most confused with
Oman	85.7	Saudi Arabia (14.3%)
Saudi Arabia	68.4	UAE (21.1%), Oman (10.5%)
UAE	70.6	Saudi Arabia (17.6%), Kuwait (11.8%)
Kuwait	71.4	Qatar (17.9%), UAE (10.7%)
Qatar	63.6	Kuwait (22.7%), Bahrain (13.6%)
Bahrain	81.8	Qatar (18.2%)

CVA achieved 73.2% overall correct classification across six populations. The highest classification accuracy was observed for the geographically peripheral populations from Oman (85.7%) and Bahrain (81.8%), while central Gulf populations showed greater morphometric overlap and lower classification rates.

**Fig 2:** Radar diagram comparing phenotypic trait profiles between coastal and inland Spilomelinae populations

Environmental correlation analysis revealed significant positive associations between population mean body size and mean annual precipitation ($r = 0.82$, $p = 0.012$) and normalized difference vegetation index ($r = 0.78$, $p = 0.022$). The correlation with mean annual temperature was not significant ($r = -0.34$, $p = 0.21$), suggesting that resource availability rather than temperature regime drives body size variation among Gulf populations [13, 14].

Discussion

The morphometric analysis presented here provides the first quantitative evidence for geographically structured

phenotypic variation among Spilomelinae populations across the Arabian Gulf region. The results reveal a pattern of body size cline that is consistent across the four species examined, with southern and environmentally more productive populations (Oman) exhibiting larger body dimensions than northern and more environmentally constrained populations (Bahrain, Qatar). This pattern does not conform to the classical Bergmann's rule prediction, as larger body size is associated with warmer, more southerly locations rather than cooler northern ones [1, 3]. Instead, the strong positive correlation between body size and precipitation-vegetation indices supports the resource availability hypothesis, which posits that insect body size scales with the quantity and

quality of nutritional resources available during larval development ^[4, 14]. In the Arabian Gulf context, precipitation and vegetation cover decline sharply from the monsoon-influenced Dhofar region of Oman northward to the hyper-arid central Gulf States, creating a productivity gradient that appears to constrain the body size of Spilomelinae populations in resource-poor environments. The particularly small body dimensions of Bahraini populations may additionally reflect an island effect, where limited habitat area and resource diversity impose size constraints beyond those explained by climatic variables alone ^[6, 9]. The moderate classification accuracy (73.2%) achieved by canonical variate analysis indicates that while populations show statistically significant morphometric differentiation, there remains substantial overlap in phenotypic space, particularly among geographically proximate central Gulf populations. This pattern is consistent with ongoing gene flow among populations connected by the dispersal capacity of adult moths across the relatively short over-water distances separating Gulf countries ^[2, 7, 10, 11]. The higher classification accuracy for peripheral populations from Oman and Bahrain suggests that geographical isolation and environmental distinctiveness promote greater morphometric divergence at the range margins ^[5, 8, 12].

Conclusion

The principal contribution of this research is the quantitative demonstration that Spilomelinae populations across the Arabian Gulf exhibit geographically structured morphometric variation that correlates with environmental productivity gradients. Supporting evidence from multivariate analyses confirms significant interpopulation differences that are most pronounced between peripheral populations and diminish among geographically central ones. From a broader perspective, these findings position Arabian Spilomelinae within the growing body of evidence linking insect body size variation to resource availability in arid environments, with implications for predicting morphological responses to climate-driven productivity changes. Outstanding questions include the relative contributions of genetic adaptation versus phenotypic plasticity to the observed variation, the fine-scale population genetic structure of Gulf Spilomelinae, and the potential for the detected morphometric cline to intensify under projected aridification scenarios.

Acknowledgements

ETY designed the comparative framework and coordinated the multi-national sampling effort; ABK performed all morphometric measurements and quality assurance protocols; MCD conducted multivariate statistical analyses; FDO managed specimen logistics and database records. The Ankara College of Applied Zoology provided stereomicroscopy facilities, digital measurement systems, and access to the entomological reference collection. This research was supported by the Scientific and Technological Research Council of Turkey. Collaborative specimen access was facilitated by partner institutions in each Gulf country. All authors contributed to interpretation and manuscript preparation.

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