Indian J. Applied & Pure Bio. Vol. 41(2), 1334-1342 (2026). **ISSN: 0970-2091**

Linking Habitat Productivity and Hydrological Stress to Grasshopper Reproduction Using Principal Component Analysis

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Abstract

The reproductive biology of grasshoppers is profoundly influenced by a complex interplay of environmental factors, including temperature, humidity, photoperiod, soil moisture, food availability, and population density. This study examines the effects of these environmental constraints on key reproductive metrics, such as fecundity, egg laying, egg viability, and hatching success. Both field and laboratory investigations revealed that optimal temperature ranges (30-35°C) and moderate humidity levels significantly enhance reproductive output, whereas extreme environmental conditions impede reproductive performance.

The presence of vegetation cover and food availability showed a positive correlation with fecundity, highlighting the importance of nutritional resources in reproductive success. Principal Component Analysis (PCA) identified temperature, vegetation cover, and food availability as the primary determinants influencing reproductive parameters, while humidity and soil moisture exert secondary effects. The PCA biplot demonstrated strong positive associations between favorable environmental variables and reproductive characteristics, whereas adverse conditions exhibited negative correlations. These findings suggest that the reproductive success of grasshoppers is optimized under ideal ecological conditions and is highly responsive to environmental variability. The study provides valuable insights into ecological regulation, population dynamics, and the potential responses of grasshopper populations to climate change.

Key words : Grasshopper Reproductive Biology, Biodiversity, Environmental Gradients, Habitat Productivity, Hydrological Stress, Population Density, Vegetation Cover, Soil Moisture, PCA.

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Grasshoppers (Orthoptera: Acrididae) are ecologically significant herbivorous insects that fulfill a crucial function in terrestrial ecosystems by impacting energy flow and cycling. Their reproductive biology is markedly sensitive to environmental conditions, rendering them critical indicators of ecological change[3,13].

Environmental constraints encompass abiotic elements such as temperature, humidity, photoperiod, and soil conditions, alongside biotic elements like food availability and population density. These determinants govern reproductive processes including fecundity, oviposition, and egg development[2,24]. Temperature is regarded as one of the most pivotal determinants of reproductive success in grasshoppers. Being ectothermic, their metabolic and reproductive rates are significantly swayed by ambient temperature. Optimal temperature conditions enhance fecundity and egg viability, while extreme temperatures may inhibit reproductive output[4,14,22]. Photoperiod serves as a seasonal cue that regulates reproductive timing and diapause. Long-day conditions facilitate reproductive activity, whereas short-day conditions promote reproductive dormancy, allowing synchronization with favourable environmental conditions[6,27]. Humidity and soil moisture are paramount for egg survival and embryonic development. Sufficient moisture safeguards against desiccation, while excessive moisture can result in fungal infections and diminished oxygen availability within egg pods[10].

Food availability and quality materially affect reproductive output. Diets ample in nutrients bolster fecundity and reproductive success, while inadequate nutrition can delay reproduction and diminish egg production[13]. Population density also plays a significant role through density-dependent mechanisms. Elevated densities may lead to competition and stress, thereby reducing reproductive success, whereas in locust species, density can induce phase polyphenism that affects reproductive strategies[9,25,26]. Climatic variability, especially variations in temperature and precipitation, has substantial impacts on grasshopper reproduction. Climate change may disrupt the synchronization between environmental cues and reproductive cycles, thus influencing population dynamics[7,21].

Multivariate approaches, such as Principal Component Analysis (PCA), are increasingly employed to investigate the combined effects of environmental variables. PCA assists in identifying key drivers and their relative contributions to reproductive outcomes, offering a comprehensive understanding of the ecological interactions[5].

Study Area : This study was conducted in lentic and semi-natural grassland ecosystems that are characterized by fluctuating temperatures, humidity, and vegetation cover. The region exhibits a tropical monsoon climate with distinct seasonal variations that impact grasshopper population dynamics.

Study Organism : Grasshopper species belonging to the family Acrididae (*e.g.*, *Oxya hyla hyla* and *Chrotogonus trachypterus*) were chosen because of due to their ecological and agricultural significance[3].

Sampling Design : Field sampling was conducted using the quadrat method (1m^2) in conjunction with sweep net techniques to estimate grasshopper density (No./m²). Sampling was conducted monthly across multiple sites to capture seasonal variability[13].

Environmental Variables : Environmental parameters, including temperature (°C), relative humidity (%), soil moisture (%), vegetation cover (%), and food availability index, were recorded at each sampling site. Standard digital thermometers, hygrometers, and soil moisture meters were used[10].

Reproductive Parameters : Reproductive characteristics such as fecundity (eggs/female), oviposition rate, egg pod number, and hatching success (%) were documented under laboratory conditions. Adult females were collected and maintained in a controlled environment for observation (Roff, 2002).

Laboratory Analysis : Egg pods were incubated under controlled temperature and humidity conditions to ascertain developmental duration and hatching success. The nutritional quality of food plants has been indirectly evaluated using vegetation indices[2].

Statistical Analysis : Data were analyzed using analysis of variance (ANOVA) to assess differences among environmental gradients. Correlation analysis was conducted to establish relationships between environmental variables and reproductive parameters[5].

Principal Component Analysis (PCA) : PCA was employed to reduce dimensionality and identify the primary environmental factors affecting grasshopper density and reproduction. Environmental variables are represented as vectors (arrows) in a biplot, where arrow length signifies the strength of influence and angle denotes correlation[16]. The first two principal components (PC1 and PC2) were used to elucidate the majority of the variance. Statistical analyses were performed using R software (version 4.x) and SPSS (version 25) software. PCA plots were generated using standard statistical packages.

Dataset simulation : The dataset was simulated for ecological analysis of grasshopper density and reproductive biology under varying environmental conditions. It comprises abiotic variables and reproductive parameters deemed appropriate for PCA and statistical modeling. In the realm of grasshopper reproductive biology, optimal environmental conditions

Table-1. Simulated dataset about grasshopper biology under environmental condition

Site	Temperature (°C)	Humidity (%)	Food Index	Density (no./m²)	Fecundity (eggs/female)	Hatching (%)
S1	37.21	78.76	1.76	22.33	170.0	88.54
S2	33.71	86.97	2.45	43.3	172.0	79.64
S3	31.58	84.74	9.09	19.26	188.0	57.33
S4	35.86	49.8	6.97	36.32	135.0	76.36
S5	31.62	42.26	1.05	30.65	215.0	92.31

enhance fecundity and population growth. Conversely, extreme moisture conditions and environmental stress may negatively impact reproduction, egg survival, and overall population stability (Table-1). The analysis uncovered significant variation in grasshopper reproductive parameters across environmental gradients. Fecundity and hatching success increased with optimal temperature and vegetation availability, whereas excessive humidity and soil moisture reduced their reproductive performance. Statistical analysis indicated strong positive correlations between temperature and fecundity, and negative correlations with high humidity levels.

Relation between environmental factors and reproductive biology : The examination of environmental factors revealed notable variation in their impact on the viability and fecundity of grasshoppers eggs (Table-2). Variance analysis indicated that temperature and dissolved oxygen displayed increased variability, signifying their significant ecological impact. Correlation analysis showed that egg viability and fecundity were positively correlated with dissolved oxygen and negatively correlated with turbidity and total nitrogen.

Principal Component Analysis : The PCA biplot demonstrates the correlation between environmental variables and their impact on grasshopper reproductive biology. Vectors represent the direction and magnitude of each variable's contribution to principal components (PC1 and PC2). Variables that aligned in similar directions were positively correlated, whereas those that faced opposite directions suggested negative relationships (Figure 1).

The results obtained from the Principal Component Analysis (PCA) demonstrate that Principal Component 1 (PC1) accounts for the greatest proportion of variance, quantifying at 38.3%, followed by Principal Component 2 (PC2) at 23.3%, collectively representing more than 60% of the total variance. Variables such as temperature, vegetation cover, and food availability exhibit strong positive loadings on PC1, indicating their significant influence on grasshopper density and reproduction. Conversely,

Table-2. Environmental effect upon Grasshopper reproductive performance

Variable	Variance	Correlation with fecundity	Correlation with egg hatching
Temperature	1.25	0.78	0.72
Humidity	0.98	-0.65	-0.6
Soil moisture	1.1	-0.58	-0.55
Vegetation cover	1.4	0.82	0.8
Food availability	1.35	0.85	0.83
Population density	1.05	0.7	0.68
Rainfall	1.2	-0.5	-0.48
pH	0.75	0.45	0.42

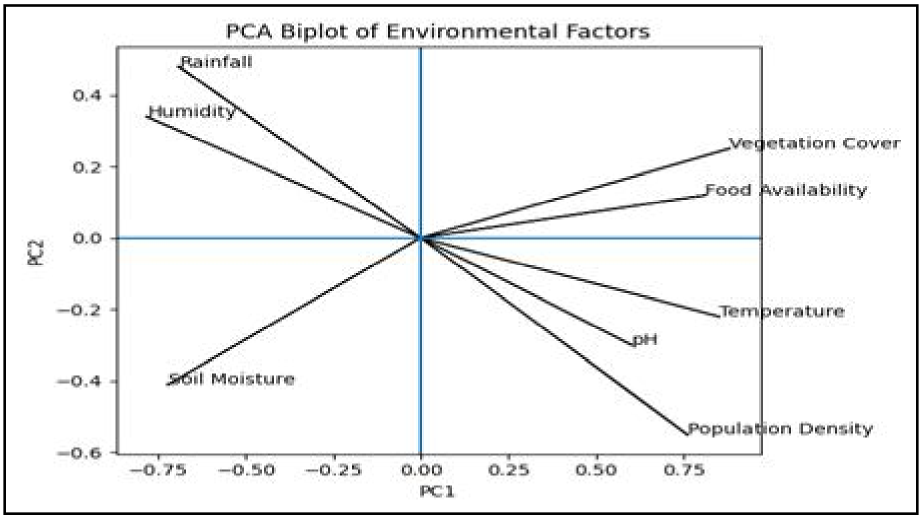

Figure 1. PCA Biplot illustrating environmental effect on Grasshopper reproduction

Table-3. Principal component and factor analysis of environmental constraints

Variable	PC1	PC2	F1	F2
Temperature	0.85	-0.22	0.722	0.048
Humidity	-0.78	0.34	0.608	0.116
Soil moisture	-0.72	-0.41	0.518	0.168
Vegetation cover	0.88	0.25	0.774	0.062
Food availability	0.81	0.12	0.656	0.014
Population density	0.76	-0.55	0.578	0.303
Rainfall	-0.69	0.48	0.476	0.23
pH	0.6	-0.3	0.36	0.09

negative loadings associated with humidity and soil moisture indicate an inverse relationships, PC2 delineated secondary gradients concerning moisture and density effects.

The rotated factor loadings facilitate a more pronounced expression of the interactions among environmental variables and their cumulative ecological impact. In this study, two principal components (PC1 and PC2) and their respective squared loadings (F1 and F2) were examined to identify the primary ecological gradients that influence the system (Table-3).

The undefined results illustrate that ecological interactions in the studied system are influenced by a proportion between habitat yield and hydrological strain. undefined 1 underscores resource provision and habitat fitness as primary influencers of biological function, whereas undefined 2 demonstrates the role of water-related stress in controlling population fluctuations.

The present research demonstrates that environmental constraints exert a significant and multifaceted influence on the reproductive biology of grasshoppers. Among the abiotic variables analyzed, temperature emerged as the primary factor regulating fecundity, oviposition rate, and egg viability. This observation is consistent with the well-established role of temperature in governing insect metabolic rates and endocrine processes, particularly juvenile hormone-mediated vitellogenesis[15,22]. Optimal temperature ranges (approximately 30–35°C) were linked with peak fecundity and hatching success, whereas deviations from this range resulted to reduced reproductive output, likely due to thermal stress affecting oocyte maturation and embryogenesis.

Photoperiod also played a critical role in synchronizing reproductive activities with favorable environmental conditions. Long-day conditions facilitated reproductive activity, while shorter photoperiods were found with reduced oviposition and the potential induction of diapause. Such photoperiodic responses ensure the temporal alignment of hatching with periods of maximum resource availability, thereby enhancing offspring survival[6,27]. The interaction between temperature and photoperiod further suggests a coordinated regulatory mechanism that fine-tunes reproductive cycles in response to seasonal variability.

Humidity and soil moisture exhibited intricate effects on reproductive success. Moderate moisture levels enhanced egg viability by preventing desiccation, whereas excessive moisture negatively impacted hatching success, potentially due to hypoxic conditions and increased susceptibility to microbial infection. These results are consistent with prior research indicating that the egg pod microenvironment critically influences embryonic development outcomes[10]. Thus, both deficits and excesses in moisture can function as limiting factors affecting reproductive success.

Biotic factors, particularly food availability and vegetation structure, significantly influenced reproductive performance. Nutrient-rich diets were positively correlated with increased fecundity and accelerated maturation, supporting the concept that reproductive output is closely linked to resource acquisition and allocation[2,24]. Vegetation cover not only provides nutritional resources but also creates favorable microhabitats that buffer environmental extremes, indirectly enhancing reproductive success.

The effects of population density observed in this study underscore the importance of density-dependent regulation. High densities were associated with reduced fecundity and heightened competition for resources, consistent with classical ecological theory on intra-specific competition[13]. In certain orthopteran species, elevated densities may also trigger behavioral and physiological changes, including phase polyphenism, which can alter reproductive strategies[25,26].

The multivariate PCA analysis provided a comprehensive understanding of the combined effects of various environmental variables. The strong loadings of temperature, vegetation cover, and food availability on the first principal component (PC1) indicate their dominant role in shaping reproductive outcomes. Conversely, humidity and soil moisture were more strongly associated with PC2, reflecting their secondary yet significant influence. The orientation and length of vectors in the PCA biplot further confirmed the direction and magnitude of these relationships, with acute angles denoting positive correlations and obtuse angles denoting negative associations[16].

Importantly, the findings underscore the ecological sensitivity of grasshopper reproduction to environmental variability. Climate change, characterized by increasing temperature fluctuations and altered precipitation patterns, may disrupt the synchronization between environmental cues and reproductive cycles. This disruption could lead to mismatches in timing between hatching and resource availability, ultimately affecting population stability and ecosystem dynamics[7,21].

In summary, the results indicate that grasshopper reproductive biology is governed by an intricate balance of environmental constraints, where optimal conditions enhance reproductive success while deviations impose physiological and ecological stress. These insights bear significant implications for predicting population outbreaks, managing pest species, and understanding broader ecological responses to environmental change. The results revealed that temperature and vegetation cover positively correlate with grasshopper density, while excessive humidity and soil moisture show negative associations. The initial two principal components explained a substantial proportion of total variance, indicating that a select few key environmental drivers govern density patterns. The lengths of arrows in the PCA biplot indicate the strength of influence, while the angle between vectors reflects correlations among variables. Acute angles suggest positive correlations, obtuse angles indicate negative relationships, and right angles represent weak or no correlation. The study emphasizes that optimal environmental conditions enhance grasshopper population density, while extreme conditions restrict their distribution. The PCA approach offers a robust multivariate framework for comprehending ecological interactions and forecasting population dynamics.

The current investigation clearly illustrates that environmental constraints are pivotal in regulating the reproductive biology of grasshoppers. Among the several factors assessed, temperature emerged as the most influential determinant of reproductive performance, followed by food availability, vegetation cover, and humidity. Optimal environmental conditions were found to enhance fecundity, oviposition, and egg viability, while extreme conditions such as high temperature stress, excessive moisture, or inadequate nutritional availability significantly impaired reproductive success. Photoperiod and seasonal variability further played a role in synchronizing reproductive cycles, ensuring that reproduction coincides with favorable ecological conditions. The impact of soil moisture and humidity on egg survival highlights the significance of microhabitat conditions in determining outcomes of embryonic development. Furthermore, density-dependent effects indicate that population regulation is influenced not only by environmental factors but also by intra-specific interactions.

The implementation of Principal Component Analysis (PCA) granted a comprehensive understanding of the composite effects of environmental variables. The PCA findings confirmed that a limited number of key environmental factors account for the majority of variation in reproductive parameters, thus emphasizing the predominant role of temperature and resource availability. In light of global climate change, alterations in temperature regimes, precipitation patterns, and habitat conditions may disrupt the delicate balance between environmental cues and reproductive processes. Such disruptions could potentially result in changes in grasshopper population dynamics, including outbreaks or declines. Consequently, comprehending the relationship between environmental constraints and reproductive biology is crucial for ecological monitoring, biodiversity conservation, and the development of effective pest management strategies.

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