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RESEARCH ARTICLE

INTEGRATION OF GIS AND REMOTE SENSING FOR STUDYING ENVIRONMENTAL IMPACTS ON INVERTEBRATE BIODIVERSITY OF DIFFERENT DISTRICTS OF PUNJAB

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Abstract The rapid environmental fluctuations occurring across various districts of Punjab have raised concerns regarding their impact on invertebrate biodiversity, which plays a vital role in maintaining ecological balance. This research aims to inspect the influence of environmental factors on invertebrate diversity using the combined application of Geographic Information Systems and Remote Sensing, addressing the deficiency of spatial biodiversity calculations in the region. Field-based biodiversity surveys were conducted to collect species data, which was then analyzed alongside satellite imagery and spatial datasets to identify areas facing ecological stress due to anthropogenic activities. GIS tools were used to map land use and land cover changes, while remote sensing helped in detecting environmental transformations such as urban expansion, deforestation, and habitat fragmentation. Evaluation was based on species occurrence and richness patterns observed across selected sites. The findings revealed a noticeable decline in invertebrate diversity in regions with high human-induced disturbances and land use conversion. The study concludes that GIS and RS are effective tools for monitoring biodiversity patterns and can support conservation planning in biodiversity-sensitive areas. Future research could expand this framework by incorporating long-term monitoring and species-level ecological modeling.

Keywords: ecological monitoring, GIS, invertebrate biodiversity, land use change, remote sensing

Introduction

The growing environmental challenges across the globe have heightened the need for advanced tools in ecological research. In this context, the integration of Geographical Information System (GIS) and Remote Sensing (RS) has emerged as a powerful approach, offering reliable techniques for analyzing spatial data and observing ecological patterns across landscapes. These technologies have redefined environmental studies by enabling detailed visual representations and accurate monitoring of biodiversity dynamics. Invertebrates, including insects, mollusks, and other non-vertebrate organisms, form the backbone of ecosystem functionality. They contribute immensely to processes like pollination, nutrient cycling, organic matter decomposition, pest control, and habitat formation, while also serving as a crucial food source

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within food webs. However, these essential species are under increasing threat due to habitat degradation, pollution, introduction of invasive species, climate change, and a range of human-driven activities. The present study aims to harness the combined power of GIS and RS to explore invertebrate biodiversity across various districts of Punjab and assess how environmental changes are influencing their existence, with the ultimate goal of guiding future conservation strategies.

GIS is a spatial analysis tool that enables the collection, organization, and interpretation of geographical data, making it indispensable for ecological monitoring and environmental planning. Remote Sensing, on the other hand, involves acquiring information about Earth's surface features using satellite imagery and aerial sensors. RS provides data on vegetation health, land cover types, temperature changes, and climatic conditions across large geographic scales and over extended periods. Together, these tools offer a comprehensive picture of how environmental variables are distributed and how they evolve, enabling researchers to correlate these changes with biodiversity indicators. For instance, RS aids in detecting habitat loss, climate variability, and land-use transformations, while GIS facilitates spatial analysis and visualization of biodiversity hotspots and threats. This integration is especially valuable in regions like Punjab, where rapid urban growth and intensive agricultural activities continue to exert pressure on natural ecosystems.

Although the ecological significance of invertebrates is well established, there remains a lack of detailed, spatially oriented studies that assess their biodiversity using modern technological approaches in Punjab. Existing research has primarily focused on vertebrate species or has lacked the spatial depth necessary for informed decision-making. By employing GIS and RS tools, this study fills a critical knowledge gap, offering insights into spatial and temporal trends of invertebrate populations and their responses to environmental stressors. Prior studies, such as those by Newbold et al. (2015) and Huang et al. (2018), have shown that anthropogenic pressures significantly affect biodiversity, but region-specific analyses using integrated technologies remain sparse. This research attempts to bridge that gap by presenting a spatial framework to monitor invertebrate diversity, analyze environmental impacts, and inform conservation interventions.

The core objectives of this research are to assess the abundance and diversity of insect species across the agroecosystems of Punjab, identify and quantify environmental variables affecting their distribution using GIS and RS, and develop a spatial model for tracking biodiversity changes over time. Additionally, the study seeks to analyze both spatial and temporal patterns in invertebrate populations and to provide recommendations for effective conservation practices. In doing so, it aims not only to advance scientific understanding but also to contribute practically to biodiversity planning and ecosystem management in a region where such insights are urgently needed.

Research Methodology

Research Framework

This study employs Geographic Information Systems (GIS), satellite imagery, and statistical analysis to assess the impact of environmental and climatic factors on invertebrate biodiversity. The following are the main elements of the framework:

Study Site Selection

The research was conducted across three districts of Punjab, Pakistan (Layyah, Faisalabad, and Multan). These districts were strategically selected due to their distinct environmental conditions, land use patterns, and varying degrees of human influence, which are key factors affecting invertebrate biodiversity (Majeed et al., 2018). By choosing geographically diverse regions, the study aimed to capture a broad spectrum of ecological variations and assess how different environmental factors impact species distribution and abundance.

Within each district, ten specific locations were identified for data collection. The selection process was based on several criteria, including environmental variability, habitat diversity, accessibility, and the occurrence of diverse land-use classifications such as agricultural fields, urban areas, and natural landscapes (Yahya et al., 2020). This approach ensured that the study encompassed a wide range of ecological settings, allowing for a more comprehensive understanding of invertebrate biodiversity patterns. By incorporating multiple locations within each district, the study provided a robust framework for analyzing how regional environmental differences influence species composition (Tikhonov et al., 2020). This site selection strategy also facilitated a comparative analysis across districts, helping to identify broader trends and localized factors contributing to biodiversity changes.

Invertebrate Species Data and Their Collection

To assess invertebrate biodiversity across the selected study sites, specimens were collected using standardized entomological techniques. A combination of sampling methods was employed to maximize species diversity and capture a representative sample of invertebrate populations.

These methods included pitfall traps for ground-dwelling insects, sweep netting for flying and vegetation-associated species, and hand collection for species that were not effectively sampled by other techniques (Harwood, 2008). This multi-method approach ensured comprehensive data collection, reducing biases associated with individual sampling techniques (Nakamura et al., 2020). Each specimen was carefully handled to maintain its structural integrity and preserve distinguishing morphological features essential for accurate identification. Collected invertebrates were properly labeled with location-specific information and transported to the laboratory for further processing. Taxonomic keys were used for classification at different hierarchical levels, including family, genus, and species (De, 2019). In cases where identification required expert validation, selected specimens were sent to the National Agricultural Research Centre (NARC) in Islamabad. Taxonomists at NARC performed detailed morphological examinations to confirm species identity, ensuring the precision and reliability of the study's findings.

This systematic approach to specimen collection and identification played a central role in understanding species distribution and abundance across different environmental settings (Isaac et al., 2020). By incorporating expert verification, the study ensured the highest level of taxonomic accuracy, strengthening the credibility of the research and providing valuable insights into invertebrate biodiversity in the region.

Remote Sensing and Bioclimatic Data

To evaluate the environmental factors influencing invertebrate biodiversity, remote sensing data were acquired using Google Earth Engine (GEE), an advanced cloud-based platform for geospatial analysis (Liu et al., 2023). A comprehensive dataset of geographic coordinates corresponding to all sampling locations was compiled and uploaded to GEE for further processing. To capture the broader environmental context surrounding each site, a 5-kilometer buffer zone was established (He et al., 2022) This approach allowed for a detailed examination of environmental conditions that could potentially impact species distribution and habitat suitability.

Within this buffer zone, satellite imagery from multiple sensors was employed to analyze a range of atmospheric and land surface parameters crucial for understanding ecosystem health. These parameters included the concentration of various gases, vegetation indices, land cover characteristics, and other essential environmental factors that could impact species distribution and habitat conditions (Li et al., 2022). By incorporating data from different satellite sources, the study enabled a detailed assessment of spatial and temporal variations in environmental conditions. This approach allowed for a clearer understanding of the impact of changes in land use, pollution levels, and vegetation cover influence invertebrate biodiversity across the selected study sites (Shukla et al., 2023).

In addition to remote sensing-derived environmental data, bioclimatic variables were gathered to examine the role of climatic conditions in shaping species richness and distribution patterns. A total of 19 bioclimatic variables (BIO1 to BIO19) were extracted, encompassing key climatic factors such as average and extreme temperatures, precipitation patterns, seasonal variations, and climate stability (Liu et al., 2023). These variables were instrumental in identifying how climatic fluctuations impact biodiversity, habitat suitability, and ecosystem resilience in different districts. By integrating both remote sensing and bioclimatic data, the study provided a comprehensive understanding of the environmental drivers affecting invertebrate communities, thereby contributing to more effective conservation and management strategies.

By combining remote sensing and bioclimatic data, this study established a comprehensive framework for understanding the environmental drivers of invertebrate diversity. This approach not only facilitated large-scale ecological assessments but also contributed toward the advancement of more effective conservation policies for preserving biodiversity in varying environmental conditions.

Statistical Analysis

To evaluate the impact of environmental and climatic factors on species biodiversity, richness, and abundance, a sophisticated statistical analysis was performed using Python (Vallat, 2018). This programming language was chosen due to its powerful computational capabilities and extensive libraries designed for data analysis and visualization (Cook et al., 2016). Several statistical tools and machine learning techniques were applied to interpret complex ecological relationships and identify key environmental drivers that influence the invertebrate biodiversity. Initially, data preprocessing was performed to organize and standardize the collected datasets. Correlation analyses were then carried out to examine the relationships between species diversity and various ecological variables, such as changes in temperature and precipitation, vegetation indices, and atmospheric gas concentrations (Lechner et al., 2020). These analyses helped identify significant trends and interactions influencing species distributions across the study sites.

To further understand habitat suitability, species distribution models (SDMs) were developed using a combination of bioclimatic and remote sensing data (Elith et al., 2009). These models allowed for the prediction of potential habitats by identifying environmental conditions that favor the presence of specific species. Advanced machine learning techniques were incorporated to improve the precision and dependability of these models.

For effective visualization of the results, various graphical representations, including scatter plots, statistical graphs, and spatial distribution maps, were generated (Sarikaya et al., 2017). These visualizations provided a clear depiction of biodiversity trends, highlighting areas with high species richness and regions where environmental stressors may impact invertebrate populations.

By employing a data-driven approach, this analytical framework facilitated a comprehensive understanding of how environmental and climatic factors shape invertebrate biodiversity. The findings not only contributed to ecological research but also provided valuable insights for conservation planning and biodiversity management in the study regions.

Results and Discussion

Average Total Specie Count by District

The figure illustrates the average total species count recorded in each district. Faisalabad exhibited the highest average, with a species count exceeding 15. In comparison, Layyah had an average species count of around 14.7, while Multan recorded the lowest, approximately 13.6. Overall, the highest number of species was found in Faisalabad.

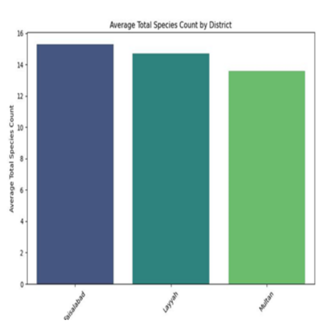

Figure 1: *Average Total Species Count by District.*

Heat Map Correlation

The heatmap illustrates a correlation analysis carried out to examine the relationship between environmental variables including atmospheric gases and bioclimatic factors—and total species richness (Klemmet al., 2015; Fick & Hijmans, 2017). The environmental variables are displayed on both the X and Y axes and include four gases (CO, CO_2, NO_2, and SO_2) and nineteen bioclimatic variables (Bio1 to Bio19). Each cell in the heatmap illustrates the correlation coefficient between two variables, ranging from -1 to +1 (Ratner, 2009). Negative values indicate an inverse relationship, positive values signify a direct relationship, and values close to zero suggest a weak or negligible correlation. Starting with CO (Carbon Monoxide), it shows the strongest negative correlation with Bio4 (-0.26), followed by Bio9 (-0.22) and Bio12 (-0.22). On the other hand, it exhibits positive correlations with Bio8 (0.12), CO_2 (0.27), and Bio5 (0.08). This indicates that CO increases slightly with variables like CO_2 and Bio8, but tends to decrease with factors such as temperature seasonality (Bio4) and precipitation-related variables like Bio12.

CO_2 (Carbon Dioxide) shows a strong positive correlation with Bio4 (0.42), Bio3 (0.38), and Bio5 (0.34). These suggest that CO_2 concentrations might increase in environments with high temperature variability and solar radiation. However, it has negative correlations with Bio19 (-0.25), Bio12 (-0.22), and Bio1 (-0.21), suggesting an inverse association with precipitation and mean annual temperature (Hamilton, 2001). NO_2 (Nitrogen Dioxide) exhibits its strongest positive relationships with Bio8 (0.09) and Bio4 (0.09), and negative relationships with Bio12 (-0.20), Bio1 (-0.21), and Bio6 (-0.20). This pattern reflects that NO_2 levels tend to be higher in regions with increased temperature variability and lower in cooler or wetter conditions.

SO_2 (Sulfur Dioxide) has positive correlations with Bio8 (0.11) and Bio4 (0.20), while its negative correlations are observed with Bio6 (-0.34), Bio9 (-0.25), and Bio1 (-0.24). The strongest negative correlation is with Bio6, indicating that higher SO_2 is associated with lower minimum temperatures of the coldest month. Among the bioclimatic variables, Bio1 (Annual Mean Temperature) shows a negative relationship with most gases, especially NO_2 (-0.21) and SO_2 (-0.24). Bio4 (Temperature Seasonality), in contrast, is positively associated with CO_2 (0.42) and SO_2 (0.20), indicating it plays a role in supporting environments with higher gas concentrations.

The total species richness variable at the bottom of the heatmap is of particular ecological interest. It demonstrates positive correlations with Bio13 (0.30), Bio18 (0.30), and Bio8 (0.22). These variables are associated with precipitation during wet periods and moderate temperatures, suggesting that more species are found in regions with favorable rainfall and temperature conditions (Hooper et al., 2005; Sala et al., 2000). Conversely, negative correlations are observed between total species and Bio6 (-0.26), SO_2 (-0.25), and Bio1 (-0.20). This means species richness declines in colder, more polluted environments (Brandle et al., 2001).

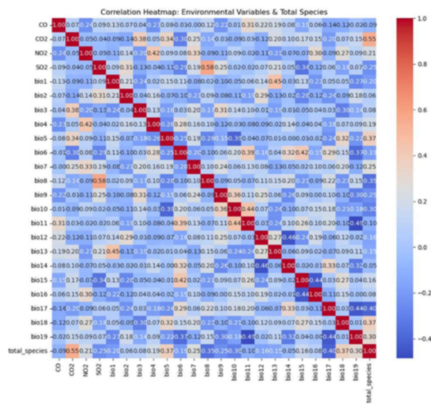

Figure 2: *Heatmap of correlation between variables and species richness.*

The scatter plot illustrates the relationship between CO concentration and total species count observed across various sampling sites. On X-axis, CO levels range from 0.5 to 3 ppm, while Y-axis displays the corresponding number of invertebrate species recorded. A noticeable clustering of data points appears around the CO concentration of approximately 1.5 ppm, shows that species abundance was generally higher when CO levels remained moderate. In this range, ecosystems appeared to support a more diverse and stable invertebrate community. However, as CO concentrations exceeded 2 ppm, a downward trend in species count became evident. The number of species recorded dropped significantly, suggesting that elevated CO levels may have a harmful impact on species richness. This pattern highlights the potential ecological stress caused by increased air pollution, specifically carbon monoxide, which may disrupt habitat quality and reduce the capacity of certain areas to support diverse invertebrate populations.

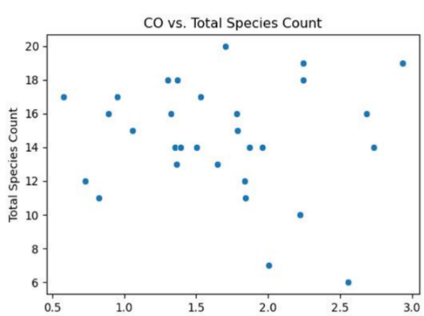

Figure 3: *Scatter plot of CO vs. total species count.*

The scatter plot shows the relationship between carbon dioxide (CO_2) concentration and total invertebrate species count across different districts of Punjab. The data suggests that as CO_2 levels increase, the number of species generally rises. The highest species count, around 20, was recorded at CO_2 concentrations between 550 and 600 ppm. This indicates a positive link between higher CO_2 levels and greater invertebrate biodiversity, though other environmental factors may also influence this pattern. One possible explanation is that increased CO_2 may promote plant growth, which in turn can enhance habitat quality and food availability for invertebrates. However, this trend might not hold if CO_2 levels continue to rise beyond ecological thresholds, potentially causing long-term changes in ecosystem balance. Therefore, while the relationship appears positive in this case, it should be interpreted with caution and in the context of broader environmental conditions. Overall, the results suggest that elevated CO_2 levels are associated with an increase in species richness, at least within the observed range.

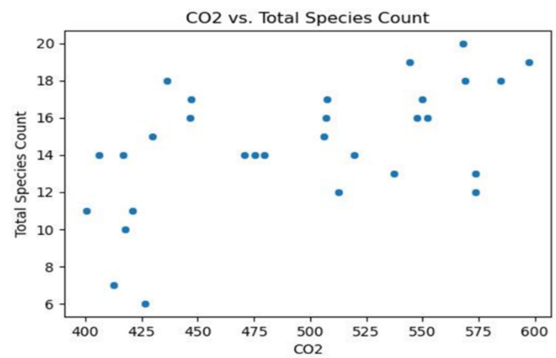

Figure 4: *Scatter plot of CO_2 vs. total species count.*

The scatter plot illustrates the relationship between NO_2 concentration and the total invertebrate species count across various districts of Punjab. While no strong or consistent linear trend is evident, the data shows that the highest species count, approximately 20, was observed when NO_2 concentrations ranged between 50 and 55 units. Beyond this range, the points appear widely dispersed, indicating a weak and scattered pattern. This suggests that NO_2 may have only a mild or indirect positive effect on species abundance. It is possible that moderate NO_2 levels correlate with urban or semi-urban environments where a mixture of vegetation and human activity could create diverse microhabitats. However, the lack of a clear trend implies that nitrogen dioxide alone is not a dominant factor and that other environmental variables may also influence invertebrate biodiversity. Therefore, NO_2 levels should be considered as part of a broader set of ecological conditions affecting species richness. Additional field-based studies incorporating seasonal changes and habitat types would help clarify this relationship. Long-term monitoring could also reveal whether invertebrate communities adapt or decline in response to persistent NO_2 exposure. Integrating remote sensing data and GIS analysis may further enhance understanding of spatial patterns in species distribution linked to air quality.

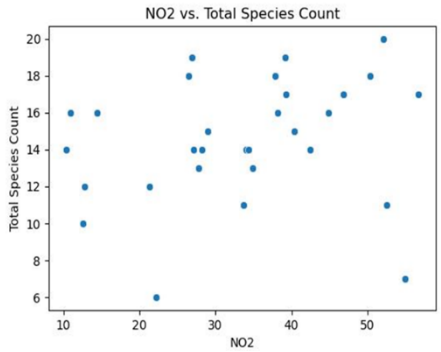

Figure 5: *Scatter plot of NO_2 vs. total species count.*

The scatter plot shows the relationship between sulfur dioxide (SO_2) concentration and the total invertebrate species count across various districts of Punjab. The data reveals a clear negative trend, suggesting that as SO_2 levels increase, the number of invertebrate species generally decreases. The highest species counts, reaching up to 20, are recorded at relatively low SO_2 concentrations, specifically between 10 and 20 units. These findings indicate that areas with cleaner air and lower SO_2 pollution tend to support greater invertebrate biodiversity. In contrast, districts with higher SO_2 concentrations display a noticeable drop in species count, with some points reflecting significantly reduced diversity. This decline in species richness at elevated SO_2 levels may be attributed to the harmful effects of the gas on both the environment and the organisms themselves. Sulfur dioxide is a known air pollutant that can damage plant tissues, alter soil pH, and reduce the availability of suitable microhabitats. Overall, the scatter plot underscores the importance of maintaining air quality, as rising levels of sulfur dioxide appear to negatively impact the health and diversity of invertebrate communities. These results highlight the need for effective pollution control measures to protect biodiversity, particularly in regions experiencing increasing industrial activity or vehicular emissions.

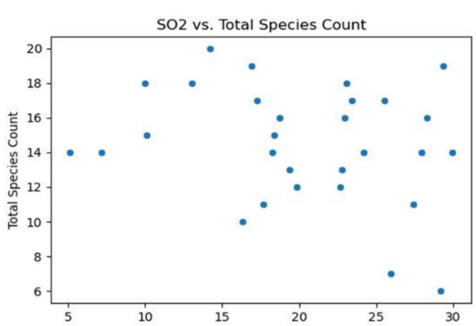

Figure 6: *Scatter plot of SO_2 vs. total species count.*

The scatter plot illustrates the relationship between the bioclimatic factor BIO1 (annual mean temperature) and the total invertebrate species count across different districts of Punjab. The data shows that as BIO1 values increase, the species count tends to slightly decline, although the data points remain somewhat scattered, indicating a weak but noticeable trend. The highest species richness, approximately 20 species, is observed at moderate annual mean temperatures ranging between 20 and 22°C. These conditions appear to offer a more favorable thermal environment that supports invertebrate survival, reproduction, and resource availability. In contrast, higher temperatures are linked with a marked decrease in species count. This decline suggests that elevated annual mean temperatures may lead to thermal stress, habitat degradation, or shifts in ecological balance, which can negatively affect sensitive invertebrate populations. Excessive heat may also influence the moisture content of soils and vegetation, further reducing habitat quality for species that rely on cooler and more humid microclimates. While some species may tolerate or adapt to warmer conditions, overall biodiversity appears to decline beyond certain temperature thresholds. These findings highlight the importance of temperature as a critical environmental driver of invertebrate diversity and emphasize the potential impacts of climate change on ecosystem health.

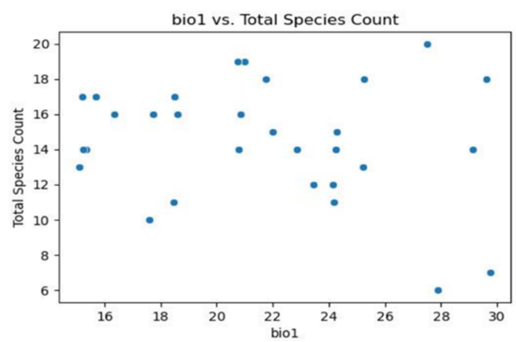

Figure 7: *Scatter plot of Bio1 vs. total species count.*

The scatter plot shows the relationship between BIO2 (mean diurnal temperature range) and the total invertebrate species count across various districts of Punjab. Although no strong or consistent linear trend is evident, the data suggests that higher BIO2 values may slightly support an increase in species count. The highest species richness, around 20 species, is observed when BIO2 values fall within the range of 8 to 10°C. This indicates that moderate daily temperature variations are more favorable for sustaining invertebrate diversity. Extremely low or high diurnal temperature ranges, on the other hand, could lead to thermal stress or unstable environmental conditions, negatively affecting sensitive species. The overall trend reveals a mild positive relationship, suggesting that ecosystems with moderate daily temperature variation tend to support richer invertebrate communities. This highlights the importance of stable yet dynamic climatic conditions in promoting biodiversity and maintaining ecological balance across different regions.

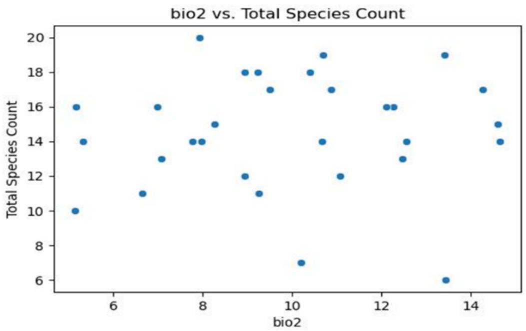

Figure 8: *Scatter plot of Bio2 vs. total species count.*

The scatter plot illustrates the relationship between BIO3 (isothermality) and the total invertebrate species count across different districts of Punjab. The distribution of points shows no strong positive or negative trend, indicating a weak or negligible relationship between BIO3 and species richness. The highest species count, around 20 species, is recorded when BIO3 values are close to 55, suggesting that moderate isothermality, where daily temperature fluctuations are not too extreme, may support greater biodiversity. This suggests that environments with more stable temperature patterns, neither too hot nor too cold, provide favorable conditions for invertebrate survival and reproduction. Extreme variations in temperature between day and night could lead to harsher conditions, which may reduce the number of suitable habitats for sensitive species. On the other hand, regions with very little temperature variation could limit ecological niches, reducing habitat complexity and the diversity of available resources.

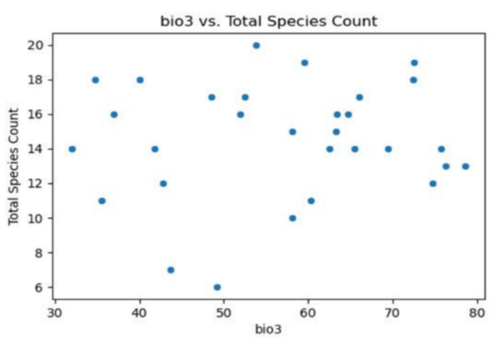

Figure 9: *Scatter plot of Bio3 vs. total species count.*

The scatter plot presents the relationship between BIO4 (temperature seasonality) and the total invertebrate species count across various districts of Punjab. The data shows a scattered pattern, indicating a weak or inconsistent relationship between temperature seasonality and species richness. The highest species count, approximately 20 species, is observed when BIO4 values range between 160 and 170, suggesting that moderate seasonal temperature variations may create conditions that support greater biodiversity. The data shows no clear trend toward increased species richness in areas with extreme temperature fluctuations. Regions with very high or very low temperature seasonality may subject invertebrates to more stressful conditions, either through excessively hot or cold temperatures, which can limit survival and reproduction rates. These extreme conditions also reduce the availability of food sources or habitat stability, making it harder for invertebrates to thrive.

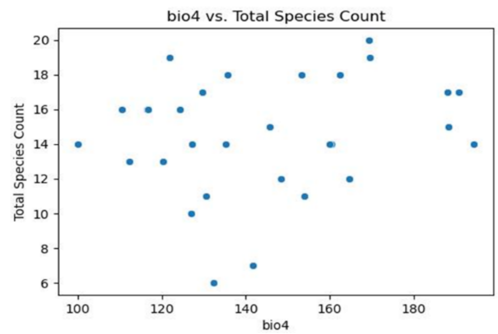

Figure 10: *Scatter plot of Bio4 vs. total species count.*

The scatter plot illustrates the relationship between BIO5 (peak temperature during the hottest month) and the total invertebrate species count across different districts of Punjab. The data shows a scattered distribution, with no strong linear trend, but several clear patterns emerge. The highest species count, approximately 20 species, is observed when BIO5 values range between 43°C and 45°C. Warmer temperatures during the hottest months could facilitate the availability of food sources, such as flowering plants and vegetation, which are essential for many invertebrate species. However, the data also suggests that beyond certain temperature thresholds, the trend becomes less predictable, implying that excessively high temperatures may have detrimental effects on species survival. In regions where temperatures are extreme for prolonged periods, invertebrates may experience stress, leading to a decrease in biodiversity. It highlights the complex relationship between temperature and species richness, suggesting that moderate to high peak temperatures during the hottest month may encourage biodiversity under certain conditions.

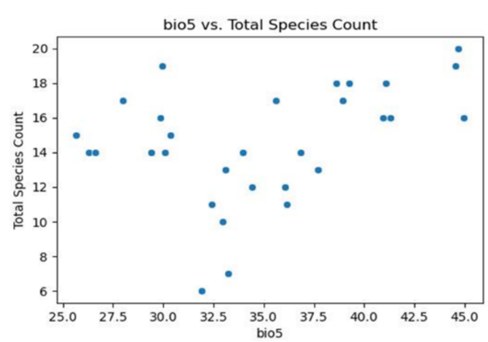

Figure 11: *Scatter plot of Bio5 vs. total species count.*

The scatter plot shows the relationship between BIO6 (lowest temperature recorded in the coldest month) and the total invertebrate species count across various districts of Punjab. The data points display a scattered distribution, with the highest species count, around 20, recorded when BIO6 values range between 5°C and 7°C. Species counts above 15 are observed across a broad range of minimum temperatures, from just below 0°C up to about 15°C. While no strong linear trend is evident, moderately warmer minimum temperatures seem to support slightly higher invertebrate diversity. This suggests that less severe winter temperatures may allow for greater survival rates, as more invertebrates are able to withstand milder conditions compared to harsher cold spells. The data also shows considerable variability, indicating that other environmental and ecological factors, such as vegetation cover, soil moisture, and overall habitat quality, likely contribute to species richness. Overall, the plot suggests that moderately warm minimum temperatures during winter create more stable conditions for invertebrates, while severe cold spells might reduce biodiversity in the region.

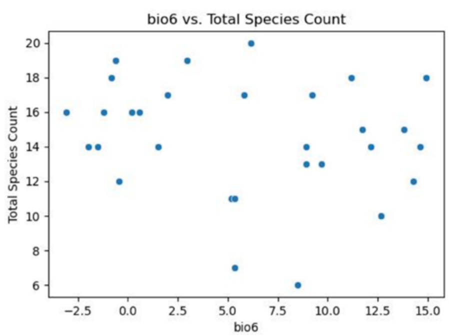

Figure 12: *Scatter plot of Bio6 vs. total species count.*

The scatter plot illustrates the relationship between BIO7 (temperature annual range) and the total invertebrate species count across various districts of Punjab. The data shows an irregular pattern, with no strong linear trend, suggesting that other environmental factors might be influencing species richness. The highest species count is recorded when BIO7 values are close to 34, indicating that a moderate annual temperature range, where temperatures are not excessively hot or cold, supports greater species diversity. In areas with low temperature variability, species might face limited habitat diversity and fewer ecological niches, while regions with high temperature variability may experience stressful conditions, especially for temperature-sensitive species. Overall, the plot suggests that moderate temperature ranges, where seasonal fluctuations are not too severe, are more conducive to supporting richer invertebrate populations, highlighting the importance of temperature stability in maintaining biodiversity.

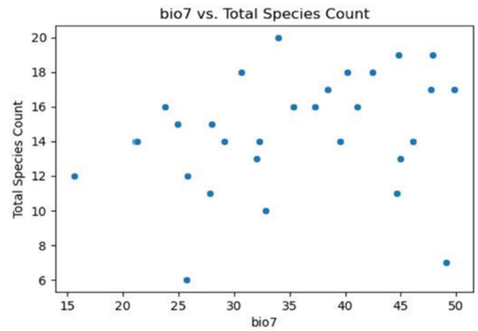

Figure 13: *Scatter plot of Bio7 vs. total species count.*

The scatter plot shows the relationship between BIO8 (mean temperature during the wettest quarter) and the total invertebrate species count across various districts of Punjab. The data reveals no clear linear trend, indicating that temperature alone may not be the sole factor influencing species richness. However, the highest species count, around 20 species, occurs when BIO8 values range between 17°C and 18°C. This suggests that moderate temperatures during the wettest quarter create conditions conducive to higher biodiversity. In these temperature ranges, invertebrates may experience favorable conditions for survival, reproduction, and foraging, which supports more diverse populations. This indicates that higher temperatures during the wettest quarter may negatively affect invertebrate species, possibly due to thermal stress or unfavorable physiological conditions for certain species. High temperatures could limit the availability of suitable habitats, reduce food resources, or increase evaporation rates, making it harder for invertebrates to thrive.

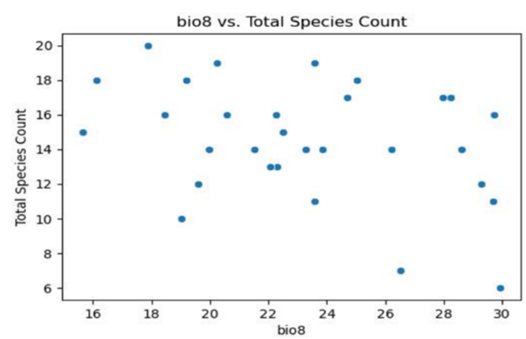

Figure 14: *Scatter plot of Bio8 vs. total species count.*

The scatter plot illustrates the relationship between BIO9 (mean temperature during the driest quarter) and the total invertebrate species count. The data shows that species count is generally higher at lower BIO9 values, with the maximum species richness, around 20 species, recorded between 11°C and 12°C. As BIO9 values rise beyond 18°C, a decline in species count becomes noticeable, with some of the lowest counts observed near 14°C and 21°C. This pattern suggests that cooler temperatures during the driest quarter favor greater invertebrate diversity, while higher temperatures may negatively impact species richness. It makes them vulnerable during periods of heat and dryness, potentially leading to reduced reproduction.

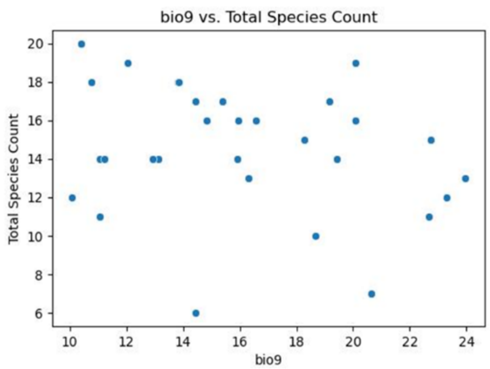

Figure 15: *Scatter plot of Bio9 vs. total species count.*

The scatter plot highlights the relationship between BIO10 (mean temperature during the warmest quarter) and the total invertebrate species count across different districts of Punjab. The highest species richness, reaching around 20 species, is recorded when BIO10 values are approximately 27–28°C. Invertebrates are generally more active in warm environments where food resources and microhabitats are abundant. As temperatures rise beyond 31°C, a decline in species count becomes evident, with the lowest counts around 6 to 7 species seen near 35°C. This indicates that excessively high temperatures may create thermal stress, reduce moisture levels, and limit the availability of suitable habitats.

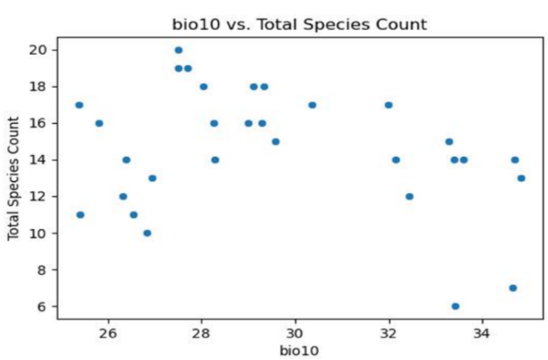

Figure 16: *Scatter plot of Bio10 vs. total species count.*

The scatter plot illustrates the relationship between BIO11 (mean temperature of the coldest months of the year) and the total invertebrate species count across various districts of Punjab. The highest species count, reaching around 20, is observed when BIO11 values are approximately 8–9°C, indicating that moderately cool winter temperatures are favorable for invertebrate diversity. In contrast, both lower temperatures (around 5–6°C) and slightly higher ones (12–14°C) are associated with reduced species counts, with some of the lowest values around 6–7 species. This suggests that temperature extremes during the coldest quarter, either too cold or too mild, may negatively impact invertebrate biodiversity.

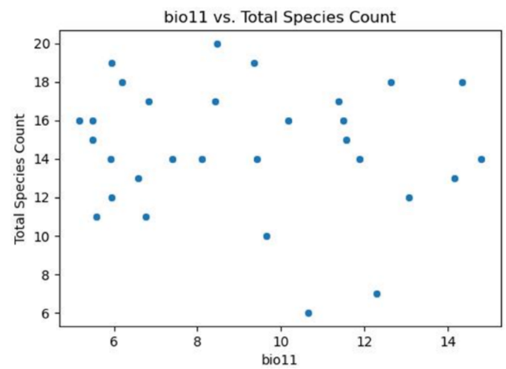

Figure 17: *Scatter plot of Bio11 vs. total species count.*

The scatter plot illustrates the relationship between BIO12 (Annual Precipitation) and the total invertebrate species count. The highest species richness is recorded when annual precipitation falls within the range of 400–500 mm. It suggests that moderate rainfall levels are most supportive of invertebrate biodiversity, likely providing balanced soil moisture and stable microhabitats that benefit a variety of species. In contrast, as precipitation increases beyond 1000 mm, a gradual decline in species count is noticeable, with some of the lowest values (around 6–7 species) observed at rainfall levels between 1000 and 1400 mm. Prolonged wet conditions may also lead to fungal growth, reduced oxygen levels in the soil, and washing away of nutrients, all of which can hinder the survival and reproduction of sensitive species. On the other hand, areas with too little rainfall may suffer from drought stress, further emphasizing the need for a balanced hydrological environment.

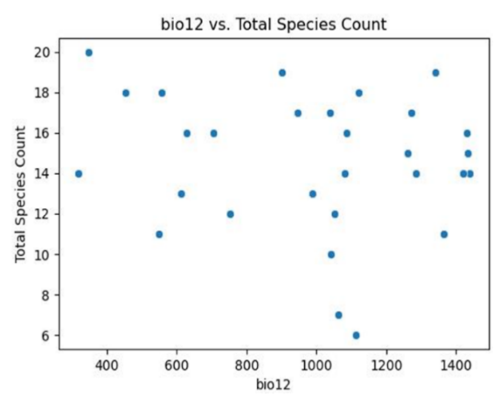

Figure 18: *Scatter plot of Bio12 vs. total species count.*

The scatter plot displays the relationship between BIO13 (Precipitation of the Wettest Month) and the total invertebrate species count across different districts of Punjab. The highest species richness, reaching around 20 species, is observed when precipitation during the wettest month falls between 180 and 200 mm. This suggests that moderate rainfall levels during this peak wet period create favorable conditions for supporting diverse invertebrate communities, likely by providing adequate moisture and supporting vegetation growth that serves as habitat or food sources. However, as precipitation exceeds 200 mm or drops below 100 mm, a noticeable decline in species count is evident, with many data points showing species counts falling below 10. Heavy rainfall may lead to flooding or soil erosion, which can destroy invertebrate habitats or displace them, while too little precipitation may fail to support necessary plant cover or soil conditions. Interestingly, some variation exists even within the favorable range, as lower species counts, ranging from 6 to 7 species, are also seen within the 150–200 mm range, possibly due to the influence of other interacting environmental stressors. Overall, the findings indicate that optimal moisture levels during the wettest period are crucial for maintaining invertebrate biodiversity, but ecological complexity can lead to varied responses even under similar rainfall conditions.

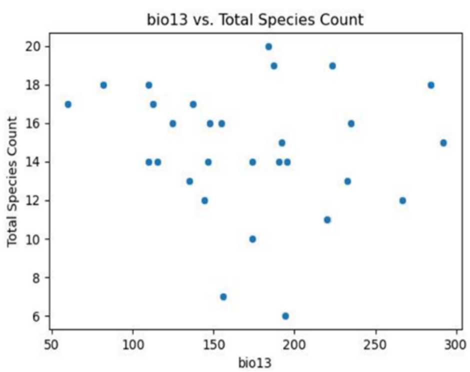

Figure 19: *Scatter plot of Bio13 vs. total species count.*

The scatter plot illustrates the relationship between BIO14 (Precipitation of the Driest Month) and the total invertebrate species count across various districts of Punjab. The highest species count is recorded when precipitation during the driest month is approximately 42–44 mm. This suggests that even during the least rainy part of the year, a moderate amount of moisture is essential to sustain invertebrate diversity. Such conditions may help maintain soil moisture, plant life, and microhabitats that many invertebrates depend on for survival, reproduction, and shelter. Very low rainfall can lead to desiccation of habitats and limit food resources, while unexpectedly high rainfall may disrupt natural seasonal cycles and create unsuitable conditions for certain species adapted to dry environments. Additionally, the scattered distribution of data points suggests that other climatic or environmental factors could also influence invertebrate populations during this time. Overall, the pattern points to the importance of balanced moisture availability, even in the driest month, for maintaining rich and stable invertebrate communities.

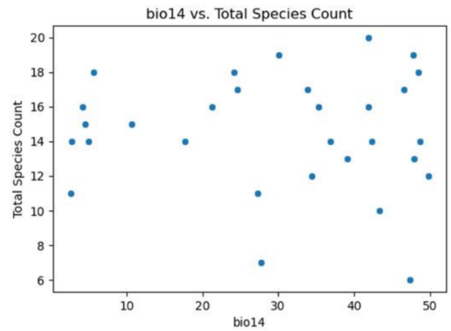

Figure 20: *Scatter plot of Bio14 vs. total species count.*

The scatter plot demonstrates the relationship between BIO15 (Precipitation Seasonality), which reflects the variability in rainfall throughout the year, and the total invertebrate species count across various districts of Punjab. The highest species counts, around 20 species, are observed when BIO15 values range between 75 and 85. This suggests that moderate to high variability in precipitation supports greater invertebrate biodiversity. Conversely, lower seasonality values (approximately 30–50) tend to correspond with fewer species. Species may benefit from seasonal changes that provide alternating periods of moisture and dryness, supporting different life stages and resource needs. On the other hand, consistently stable precipitation may limit ecological niches and reduce opportunities for adaptation and diversification. The scattered nature of the data also implies that while BIO15 plays a role, other climatic and environmental factors likely influence species richness.

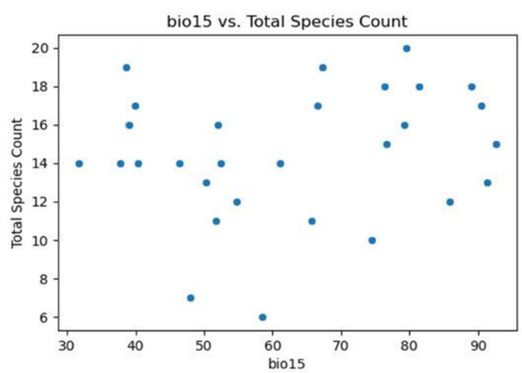

Figure 21: *Scatter plot of Bio15 vs. total species count.*

The scatter plot illustrates the relationship between BIO16 (Precipitation of the Wettest Quarter) and the total invertebrate species count across different districts of Punjab. The highest species richness, around 20 species, is observed when BIO16 values lie between 300 and 350 mm, suggesting that moderate precipitation during the wettest quarter creates favorable conditions for invertebrate diversity. However, as precipitation exceeds 500 mm, species counts tend to decrease slightly or become more variable, indicating that excessively high rainfall may not contribute to further increases in biodiversity. Very high precipitation levels might also influence vegetation structure or microhabitats in ways that are less suitable for many species. On the other hand, consistent and moderate rainfall during the wettest quarter may help sustain food availability and shelter, supporting a stable and diverse population.

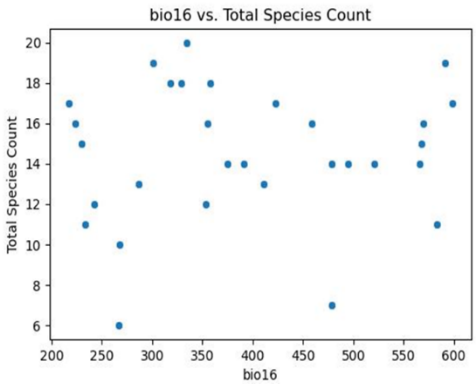

Figure 22: *Scatter plot of Bio16 vs. total species count.*

The scatter plot highlights the relationship between BIO17 (Precipitation of the Driest Quarter) and the total invertebrate species count across various districts of Punjab. The highest species richness, approximately 20 species, is observed when BIO17 values fall between 45 and 50 mm, suggesting that moderate rainfall during the driest quarter creates more favorable conditions for invertebrate diversity. This level of precipitation likely helps maintain basic moisture levels in soil and vegetation, which are essential for sustaining invertebrate habitats even during dry periods.
In contrast, both very low precipitation (below 20 mm) and unusually high rainfall (above 80 mm) are associated with more scattered and generally lower species counts. Excessively dry conditions may limit resource availability, causing habitat desiccation, while too much rainfall might lead to waterlogged or unstable environments, both of which can be unfavorable for many invertebrate species. These findings suggest that a balanced level of rainfall during the driest quarter plays a critical role in supporting stable and diverse invertebrate communities. Moderate moisture during these months not only aids survival but also enhances reproductive success, ensuring population continuity. It also maintains microclimatic stability, which is vital for sensitive and small-bodied organisms like invertebrates.

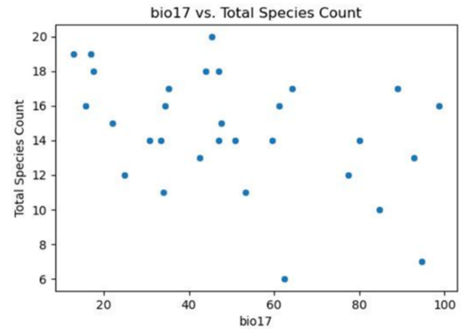

Figure 23: *Scatter plot of Bio17 vs. total species count.*

The scatter plot illustrates the relationship between BIO18 (Precipitation of the Warmest Quarter) and the total invertebrate species count across different districts of Punjab. The highest species count, reaching up to 20 species, is observed when BIO18 values range between 250 and 270 mm, indicating that moderately high rainfall during the warmest months supports greater biodiversity. In contrast, lower precipitation levels (around 100–150 mm) are generally associated with reduced and more variable species counts.
This pattern suggests that adequate rainfall during the hottest period positively influences invertebrate diversity, likely by maintaining soil moisture, supporting vegetation growth, and providing suitable microhabitats for survival. Consistent moisture availability during warm months supports the life cycles of various invertebrates, including reproduction, feeding, and larval development. On the other hand, inadequate rainfall during this quarter may lead to drying of aquatic habitats and degradation of vegetation, resulting in a decline in suitable niches and food resources. Such type of conditions could particularly affect the soft-bodied invertebrates or some aquatic invertebrates, that depend heavily on moisture.

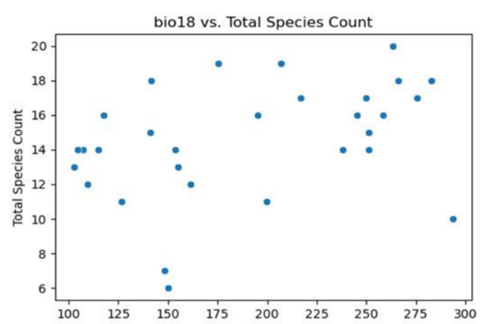

Figure 24: *Scatter plot of Bio18 vs. total species count.*
The scatter plot depicts the relationship between BIO19 (Precipitation of the Coldest Quarter) and the total invertebrate species count across districts of Punjab. The highest species richness, peaking at 20 species, is observed when precipitation levels range

between 140 and 160 mm. This suggests that moderate rainfall during the coldest quarter provides suitable environmental conditions that support greater invertebrate biodiversity. In contrast, the areas receiving lower precipitation show a noticeable decline in species count. These findings imply that sufficient moisture during the colder months may help maintain soil humidity, food sources, and shelter, which are vital for the survival and reproduction of various invertebrate species. Drier winters, on the other hand, may lead to harsher conditions, reducing the availability of suitable habitats and ultimately impacting species richness. Overall, the analysis highlights the importance of seasonal precipitation in shaping invertebrate community patterns across different ecological zones.

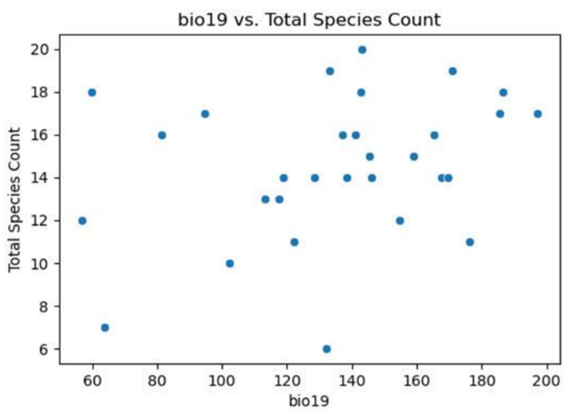

Figure 25: *Scatter plot of Bio19 vs. total species count.*

Discussion

The relationships between environmental factors and invertebrate species richness across Punjab highlight the significant roles of both pollution and climate in shaping biodiversity patterns. Elevated concentrations of pollutants such as CO and SO_2 are negatively correlated with species richness, reflecting habitat degradation and physiological stress documented in prior studies (Bishop et al., 2002; Roy et al., 2003). Conversely, higher CO_2 levels may enhance plant productivity, indirectly benefiting invertebrate communities through improved food and habitat availability, a phenomenon also observed in CO_2 fertilization research (Zvereva & Kozlov, 2006). The complex and weak relationship with NO_2 likely reflects local variations in land use and habitat heterogeneity, consistent with regional biodiversity assessments (Haddad et al., 2015). Furthermore, increased temperatures, particularly annual mean temperature (BIO1), correspond with declines in species richness, supporting global concerns regarding thermal stress on ectothermic organisms (Deutsch et al., 2008).

Temperature-related bioclimatic variables (BIO2–BIO5) further clarify climate–biodiversity dynamics, where moderate temperature ranges and seasonality tend to support richer invertebrate communities. Optimal species richness is associated with moderate diurnal temperature variation, isothermality, and seasonal stability, which create thermally diverse but stable microhabitats conducive to survival (Roy et al., 2003; Deutsch et al., 2008). However, extreme heat during the hottest month (BIO5) reduces diversity by exceeding physiological thresholds, confirming that climatic extremes constrain ecological resilience (Bishop et al., 2002).

Precipitation patterns (BIO12–BIO19) reveal that balanced and moderate rainfall throughout the year is critical for sustaining invertebrate biodiversity. Optimal species richness corresponds with moderate annual and seasonal precipitation levels that maintain soil moisture, vegetation structure, and microhabitats essential for invertebrate survival and reproduction. Both drought-like low precipitation and excessive rainfall lead to habitat degradation, such as desiccation or waterlogging, which negatively impact species richness (Roy et al., 2003). These results underscore the importance of both the amount and timing of precipitation in maintaining ecological stability.

Overall, this integrated analysis affirms the multifactorial influences of climatic and pollution stressors on invertebrate diversity in Punjab, emphasizing the value of GIS and remote sensing tools for spatial biodiversity assessment and conservation planning. Understanding these relationships is essential for predicting biodiversity responses under future climate change scenarios and for guiding effective ecosystem management.

Author Contributions

Rabia Yousaf designed the study, collected and analyzed data, and drafted the manuscript. Muhammad Naeem (supervisor) and Maryam Riasat (faculty member) oversaw the study and reviewed the manuscript. All authors approved the final version.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

Acknowledgment

This work is part of research.

Data Availability

Data will be made available on request.

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