Geostatistical Study on the Spatial Distribution of Larvae and Adults of the Brown Stem Longhorn Beetle Postprint

Authors: Chen Qian, Xu Zhichun, Zhang Liansheng, Lu Pengfei, Zhang Yongfu

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Abstract

Arhopalus rusticus Linnaeus is a highly destructive wood-boring pest that severely damages pine, fir, cypress and other forest trees, primarily attacking weakened coniferous trees and standing dead trees after fires, and is the wood-boring pest with the strongest ability to carry Bursaphelenchus mucronatus after Monochamus alternatus. To better control its damage, we conducted an in-depth study of its population spatial pattern, using geostatistical methods to analyze the spatial distribution characteristics of Arhopalus rusticus larvae and adults in three Pinus tabuliformis forests with different damage levels. The results showed that the damage caused by Arhopalus rusticus differed significantly among the three forest stands with different damage levels, with an infested tree rate of 30.8% in lightly damaged stands, 44.3% in moderately damaged stands, and as high as 78.3% in heavily damaged stands. Based on the analysis of variogram curves, the optimal fitting models for the spatial distribution of Arhopalus rusticus larval populations in lightly damaged, moderately damaged, and heavily damaged forests were the Gaussian model, Gaussian model, and exponential model, respectively, while the optimal fitting models for adult population spatial distribution were all linear models. The number of Arhopalus rusticus larvae showed obvious spatial dependence in all three stand types, with spatial dependency ranges of 19.10, 11.97, and 61.98 m in lightly damaged, moderately damaged, and heavily damaged forests, respectively, and spatial continuity intensities of 0.646, 0.784, and 0.500, respectively; the spatial dependency ranges for adults were 43.08, 43.23, and 44.17 m, respectively, with spatial continuity intensities of 0.044, 0.021, and 0.171, respectively, but the number of adults showed a random spatial distribution without exhibiting spatial dependence. Based on the analysis of vertical distribution diagrams, Arhopalus rusticus larvae and adults on Pinus tabuliformis mainly concentrated and aggregated at certain heights, and then their density decreased with increasing height, also decreasing as the height approached the ground. Spatial distribution maps generated using the Kriging interpolation method showed that larvae had obvious aggregations in spatial distribution, with aggregation centers mainly concentrated in the forest center, spreading from the central trees to the entire forest, while adults showed a random distribution.

Full Text

Preamble

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Geostatistical Analysis of the Spatial Distribution of *Arhopalus rusticus* Larvae and Adults

Chen Qian[1], Xu Zhichun[1]*, Zhang Liansheng[2], Lu Pengfei[1], Zhang Yongfu[3]
[1]Beijing Forestry University, [2]Jianping County Forestry Bureau of Liaoning Province, [3]Beijing Ming Tombs Forest Farm

Abstract

Arhopalus rusticus is a devastating wood-boring pest that inflicts severe damage on coniferous species such as pines and cypresses, primarily attacking weakened conifers and standing dead wood following fires. As the most efficient vector of the pinewood nematode *Bursaphelenchus mucronatus* after *Monochamus alternatus*, this species poses a significant threat to forest health. To develop effective control strategies and characterize its population spatial structure, we employed geostatistical methods to analyze the spatial distribution patterns of *A. rusticus* larvae and adults in three *Pinus tabuliformis* stands experiencing light, moderate, and heavy infestation.

The infestation intensity varied significantly among stands, with 30.8% of trees infested in the lightly damaged stand, 44.3% in the moderately damaged stand, and 78.3% in the heavily damaged stand. Variogram analysis revealed that Gaussian models optimally described larval spatial distribution in lightly and moderately infested stands, while an Exponential model best fit the heavily infested stand. In contrast, Linear models were most appropriate for adult populations across all damage levels.

Larval counts exhibited strong spatial dependency in all three stands. The spatial dependency ranges were 19.10 m, 11.97 m, and 61.98 m for light, moderate, and heavy infestation, respectively, with corresponding spatial continuity intensities of 0.646, 0.784, and 0.500. Adult populations showed dependency ranges of 43.08 m, 43.23 m, and 44.17 m, but their numbers were spatially random without significant spatial autocorrelation.

Vertical distribution analysis demonstrated that both larvae and adults concentrated at specific heights on host trees, with density decreasing both above and below these optimal zones. In lightly infested stands, larval density peaked at 24–25 cm height, while adults peaked at 4–5 cm. In moderately infested stands, peaks occurred at 9–10 cm for larvae and 26–27 cm for adults. In heavily infested stands, maximum densities were observed at 13–14 cm for larvae and 5–6 cm for adults.

Kriging interpolation generated spatial distribution maps showing pronounced larval aggregation centered in the middle of stands, spreading outward toward stand edges. Adults, however, displayed random spatial patterns. These findings provide critical insights for targeted monitoring and management of this destructive pest.

Keywords: *Arhopalus rusticus*; spatial distribution; larvae; adults

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Introduction

All populations are distributed across space, and due to interactions among individuals and environmental adaptation, the same species exhibits distinct spatial patterns under different conditions. Spatial pattern represents a fundamental characteristic of insect populations, determined by both environmental conditions and biological traits. Investigating these patterns not only reveals intra- and interspecific spatial configurations but also provides reliable foundations for sampling design and population forecasting. In China, geostatistical approaches have achieved considerable success in entomological research, making them increasingly favored by scientists for exploring insect population spatial structure.

Arhopalus rusticus (Linnæus) is a particularly destructive wood-boring pest of pines and cypresses. Research indicates that *A. rusticus* individuals carry *Bursaphelenchus mucronatus* with high efficiency—second only to *Monochamus alternatus*. Because *B. mucronatus* is closely related to the pine wood nematode (*B. xylophilus*) in morphology and behavior, *A. rusticus* may also vector this even more destructive pathogen. Large populations of *A. rusticus* are commonly found in stumps and dying bark of fire-damaged pines. To better understand its population dynamics and provide scientific support for surveys and forecasting, this study applies geostatistical methods to investigate the spatial distribution of its larvae and adults.

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1. Study Site Description

The study was conducted in a *Pinus tabuliformis* forest in Qingsongling Township, Jianping County, Liaoning Province, with geographic coordinates of

41°80 N, 119°84 E. The region has an average annual precipitation of 487 mm and mean temperature of 5.7°C. Forest vegetation is dominated by Pinaceae species, with forest coverage being extensive. Three plots with different damage levels were selected within the *A. rusticus*-infested forest area in 2016.

2. Survey Methods

Based on plot size and tree distribution, we established three 90 m × 30 m sample plots. A complete census sampling method was employed, counting frass holes (representing larvae) and emergence holes (representing adults) on each tree from base to crown in each 1-meter height interval. The relative spatial coordinates of every *P. tabuliformis* tree within each plot were recorded on graph paper.

3. Vertical Distribution Analysis

The vertical distribution patterns of *A. rusticus* larvae and adults across the three plots were analyzed and visualized using Excel.

4. Semivariogram Analysis

The semivariogram is a unique geostatistical tool that describes both the spatial structure and random variation of regionalized variables. For a regionalized variable $Z(x)$, the semivariogram (h) for points separated by distance h is calculated as:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2$$

where $N(h)$ is the number of sample pairs at separation distance h. The semivariogram plot displays values against distance h. Key parameters include: the **nugget** (C), representing microscale variability and measurement error; the **sill** ($C + C$), indicating total spatial variance; and the **range** (A), defining the distance over which data are spatially correlated. Within the range, data exhibit correlation; beyond it, points are independent.

5. Theoretical Variogram Model Fitting

Common theoretical models—including Linear, Exponential, and Spherical—can fit empirical semivariograms. A pure nugget variogram, showing no spatial correlation at any distance, indicates random distribution. During model fitting, different theoretical models should be tested, selecting the optimal function based on coefficient of determination (R^2) and residual sum of squares (RSS). The appropriate model is chosen by comparing range and nugget values.

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6. Generation of Spatial Distribution Maps

Kriging, a core component of geostatistics, estimates values at unsampled locations through weighted averaging of known data points. Weights ( ) are assigned based on spatial relationships between the estimation point and sample locations, as well as the variable' s spatial autocorrelation. The estimator is:

$$\hat{Z}(x_0) = \sum_{i=1}^{n} \lambda_i Z(x_i)$$

After selecting the optimal variogram model, Kriging interpolation was performed using Surfer 8.0 software to generate spatial distribution maps for *A. rusticus* larvae and adults.

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7. Results

7.1 Stand Characteristics and Infestation Levels

Basic stand information and infestation data are summarized in . The three stands showed markedly different infestation intensities, with tree infestation rates of 30.8%, 44.3%, and 78.3% for light, moderate, and heavy damage levels, respectively.

7.2 Vertical Distribution of Larvae

Larvae exhibited distinct vertical distribution patterns across damage levels ([Figure 2: see original paper]). In lightly infested stands, density peaked at 24-25 cm height, while moderately infested stands showed a maximum at 9-10 cm. Heavily infested stands had the highest density at 13-14 cm. Although minor secondary peaks occurred at some heights, the general pattern showed decreasing density both above and below the primary peak.

7.3 Vertical Distribution of Adults

Adults also displayed clear vertical stratification ([Figure 3: see original paper]). Peak densities occurred at 4-5 cm in lightly infested stands, 26-27 cm in moderately infested stands, and 5-6 cm in heavily infested stands. As with larvae, density generally decreased with distance from the optimal height in both directions.

7.4 Spatial Distribution Analysis of Larvae

Geostatistical analysis of larval populations across the three stands yielded the parameters shown in . In lightly infested stands, the variogram was best fit by a Gaussian model with $R^2 = 0.708$, indicating strong spatial aggregation. The spatial dependency range was 19.10 m, with spatial continuity intensity of 0.646, meaning 64.6% of total variance was attributable to spatial autocorrelation. The relatively low nugget value (0.0194) suggests minimal measurement error. Contour and vector overlay maps revealed several distinct aggregation centers, with larval density decreasing outward from these centers, reflecting aggregation intensity and diffusion direction ([Figure 4: see original paper]).

In moderately infested stands, a Gaussian model also provided the best fit ($R^2 = 0.837$), with a dependency range of 11.97 m and higher spatial continuity intensity (0.784). The increased nugget value (0.332) may result from human activities such as wood cutting, which reduces weakened host trees, combined with high elevation and abundant large rocks affecting larval distribution. Aggregation centers were clearly visible, showing similar diffusion patterns ([Figure 5: see original paper]).

Heavily infested stands were best described by an Exponential model ($R^2 = 0.749$) with the largest dependency range (61.98 m) but lower spatial continuity intensity (0.500). The substantial nugget value (1.209) likely reflects human tree removal and experimental nematode introduction activities near the plot. Despite these disturbances, aggregation centers remained identifiable, with density gradients radiating outward ([Figure 6: see original paper]).

7.5 Spatial Distribution Analysis of Adults

Adult spatial distribution analysis yielded the parameters in . All three stands showed Linear models with very weak aggregation, approaching random distribution. Spatial dependency ranges were 43.08 m, 43.23 m, and 44.17 m for light, moderate, and heavy infestation, respectively. However, spatial variation ratios (C/Sill) were only 0.044, 0.021, and 0.171, indicating that just 4.4%, 2.1%, and 17.1% of total variance derived from spatial autocorrelation. The high nugget proportions (95.6%, 97.9%, and 82.9%) and variograms approaching pure nugget effects confirm that adult distributions were essentially random. Large nugget values likely resulted from peak adult emergence timing, grazing disturbances, and sampling errors. The variogram curves ([Figure 7: see original paper]) showed minimal change with distance, suggesting that factors like uniformly distributed weakened trees and strong adult flight capability produced near-random spatial patterns.

8. Conclusions and Discussion

The *A. rusticus* life cycle in China spans two years, with each larva producing only one frass hole during its entire development period. Therefore, using frass hole counts as a survey index is accurate and reliable. Adults emerge through a single exit hole. This study represents the first application of geostatistics to analyze *A. rusticus* larval spatial patterns.

Our results demonstrate that larval spatial distribution exhibits clear aggregation across all three damage levels, though specific patterns vary. The optimal variogram models were Gaussian for light and moderate stands and Exponential for heavy stands. All stands showed several distinct aggregation centers from which larval density decreased outward, indicating diffusion from central foci. Since larvae lack independent dispersal capability, adult flight behavior and oviposition preferences are primary determinants of larval spatial patterns. Host tree characteristics such as height and diameter also influence population spatial features.

Field observations revealed that adults do not feed after emergence. Upon reaching sexual maturity, females select weakened or recently dead trees for oviposition, with some even depositing eggs in soil. The distribution of weakened and newly dead trees thus strongly correlates with *A. rusticus* aggregation patterns, matching the aggregation centers identified in our spatial maps. As damage intensity increases, the number of aggregation centers also increases.

In contrast, adult variograms approached pure nugget effects across all stands, indicating spatial randomness. While spatial maps showed a few weak aggregation points, the overall distribution was uniform. The large nugget values and minimal spatial dependency suggest that sampling scale critically affects variogram parameters. Future studies should expand sampling extents to more comprehensively analyze spatial patterns.

The vertical distribution patterns show that both larvae and adults concentrate at specific heights, with density decreasing above and below these zones. Infestation levels significantly affect total numbers but not the fundamental vertical stratification. For management, control efforts should focus on the tree base where densities are highest, optimizing efficiency and reducing costs. Identifying aggregation centers and controlling along diffusion pathways will enhance effectiveness.

Integrated management strategies should combine physical, chemical, and biological methods. During oviposition periods, manual egg destruction significantly reduces damage rates. Spraying pyrethroid emulsions on infested trees or in areas with high adult activity can effectively prevent new attacks and kill emerging adults. Biological control using egg parasitoids or *Scleroderma guani* wasps during larval stages also shows promise. Additionally, mixed planting of non-host species with susceptible conifers may reduce infestation risk.

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