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RESEARCH ARTICLE

Spatial distribution of *Holcocerus hippophaecolus* (Lepidoptera: Cossidae) pupae in a seabuckthorn (*Hippophae rhamnoides*) stand

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Abstract The seabuckthorn carpenter moth, *Holcocerus hippophaecolus*, which has a generation time of four years, is recently becoming one of the major pests of the seabuckthorn (*Hippophae rhamnoides*) in Inner Mongolia, Liaoning, Shanxi, Ningxia and Shaanxi of China (Hua et al., 1990). The larvae of the *H. hippophaecolus* mainly damage the stems and roots of the seabuckthorn, and the mature larvae pupate in the soil. The spatial distribution of the pupae was analyzed by using biostatistics and geostatistics in order to effectively control the insect and further study the spatial distribution of the population. Results show that most of the pupae (90%) had an eclosion time span from early June to the end of July. The sex ratio of the pupae was nearly 1:1 in the woodland samples. In addition, 24.3% of the 971 trees investigated had pupae and it ranged from 0 to 4 per tree within a distance of 1.3 m from the base of the stem. 90% of the pupae were aggregated within a distance of 1 m from the base of the stem. The pupae show intense spatial aggregation in the sampled woodland which had an 11.1 m spatial dependence and a 90.7% intensity in the local spatial continuity. Moreover, the population presented an intensive spotted distribution and many aggregated spots were found in the woodlands. As for the relationship between grid size and variogram of the pupae, the variations in the range, the intensity of local spatial continuity and the sill were all very low or non-existent when the grid size was 5 m, 6 m or 7 m. Whereas, the value of the decisive coefficient was the biggest when the grid size was 5 m making it the ideal grid size.

Keywords *Holcocerus hippophaecolus*, *Hippophae rhamnoides*, pupae, spatial distribution, geostatistics

1 Introduction

The seabuckthorn carpenter moth, *Holcocerus hippophaecolus* (Hua et al., 1990) (Lepidoptera: Cossidae) has recently become a major wood-boring pest for seabuckthorns (*Hippophae rhamnoides*) in Inner Mongolia, Liaoning, Shanxi, Ningxia and Shaanxi of China. The larvae mainly damage the stems and roots of the seabuckthorn. In some areas, the trees were withered because their roots were destroyed by larvae (Zhou, 2002; Luo et al., 2003a; 2003b; Jia et al., 2004; Lu et al., 2004; Zong et al., 2004a; Zong et al., 2004b; Zong et al., 2005). The generation time of *H. hippophaecolus* is four years and the mature larvae usually pupate underground 10 cm around the base of the stem. Some of the pupae show up partially from the soil, while others are exposed on the surface making them easy to find. Female moths usually lay their eggs into the crevices and wounds of stem barks and sometimes on the branches. However, the egg-laying sites are dependent on the growth status of the seabuckthorn tree.

The larvae aggregate together numbering several to hundreds and damage the seabuckthorns. The damage to the tree can be classified into two types: the newly-hatched larva bore the phloem of the stem, and later instar larvae crawl from the stems to the epidermis of roots.

The spatial distribution pattern is one of the most important characteristics of an insect population which is a result of the interaction and co-evolution of biological characteristics with the conditions in the specific habitat. It is very necessary to study the spatial patterns of the insect in order to understand its ecological adaptability and important to reveal the spatial structure of populations and sub-populations which is helpful in enhancing sampling techniques, forecasting the tendency of the population density and for developing preventive and control strategies against pests (Zheng and Xia, 1993;

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Ding, 1999 3). In the study of spatial patterns, traditional biostatistical methods provide qualitative information about the spatial distribution and less information of in the exact position and extent of the population distribution. The geostatistical method, however, not only can quantify the spatial autocorrelation of the regional variables, but can also estimate the non-sampled locations and simulate the spatial distribution which has fundamentally changed the theoretical system of traditional biostatistics based on the random sampling method. A detailed study on the spatial pattern of *H. hippophaecolus* larvae and eggs using geostatistics was carried out in 2003 (Zong et al., 2005). But, the spatial pattern and population dynamics of the pupae have not been reported so far. In the present study, the spatial distribution of *H. hippophaecolus* pupae was investigated by using the geostatistical method (Hohn et al., 1993; Zhou and Xu, 1997; Li et al., 1997; Shi and Li, 1997; Wang, 1999; Wright, 2002; Yünsel et al., 2002). This can provide new theoretical tools and instructions for suitable control methods, forecasting of the population density and for sampling techniques.

2 Materials and methods

2.1 Study area

We selected Jianping County, located in the western part of Liaoning Province, as our study area. This region is mainly covered by small hills. It belongs to the transitional belt from the Mongolia plateau to the Songliao plain. The climate is the continental monsoon climate with an annual average precipitation of 487 mm. The terrain declines from the northern part to southern part. The annual average temperature is 5.7°C. The largest seabuckthorn forest of the world is in Jianping County which is approximately 68500 hm^2, including the original seabuckthorn forest of 40000 hm^2 mainly distributed in the northern part of Jianping. At the beginning of July in 2004, the spatial pattern of the *H. hippophaecolus* pupae was investigated in the seabuckthorn forest in Jingoumen village. The seabuckthorns were 20 years old. A space of 1 × 2.5 m was used in the sampling field. The average diameter of the trees at chest height was 5.42 cm and the average height was 3.60 m.

2.2 Methods

2.2.1 Field measurements

One sample plot with the size of 70 m × 70 m was selected in the seabuckthorn forest in 2004. 971 trees were studied. There are three sampling steps: 1) the actual spatial location of each seabuckthorn tree was recorded on the coordinate paper, 2) the number of female and male pupae present in the experimental field was counted every five days, and 3) the actual location of each pupa in relation to the base of the stem was recorded on the coordinate paper. The study was continued until the end of August when no new pupae appeared. 306 pupae were collected.

2.2.2 Statistical methods

Variance is the difference between two random samples which have equal separation distance. Supposing that the regional variable Zi and $Zi+h$ respectively refer to the observed values of two samples with h separation distance, in the whole sample space, the spatial correlation between two samples with h separation distance can be denoted by the function

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

Where $N(h)$ is the pair of sample spots with separation distance h, a variogram can be obtained by taking $\gamma(h)$ to h and charting it. As shown in Fig. 1, there are three important parameters in the variogram: nugget, sill and range. The nugget is the value of the variogram at zero separation distance which reflects the possible extent of the random interior of the regional variable. The range is the separation distance where the variogram reaches a balance, indicating the affected scope of the regional variable. The sill is the value of the variogram which reaches the balance at the range and means the diverse extent of the regional variable.

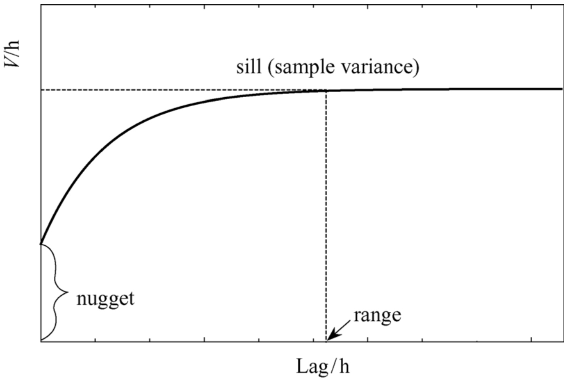


Fig. 1 A typical variogram

In geostatistics, many kinds of theoretical models have been chosen to fit the actual variogram, such as the spherical, exponential, Gaussian, linear with sill and linear without sill (Zhou and Xu, 1997; Wang, 1999). The interpretability of a model can be judged, firstly, by considering the size of decisive coefficient R^2, then the residual sum of square *RSS* and finally the range and nugget (Wang, 1999). It was found that the spatial pattern of the *H.*

hippophaecolus pupae was fitted with the exponential model by combining the investigated data and comparing several theoretical models.

3 Results

3.1 Population dynamics of the *H. hippophaecolus* pupae

The time of the pupal appearance is the same as that of the adults' emergence. Previous studies show that the moths emerged from early June to the end of August with two peaks of eclosion. The first peak of emergence was during ten days in the middle of June and the second during the last ten days of July. Here, the statistical analysis indicated that the number of the pupae was 119 (38.9%) in June, 154 (50.3%) in July and 33 (10.8%) in August. Nearly 90% of the pupae appeared from early June to the end of July and about one half of the pupae appeared in July. In other words, the number of moths in the second emergence peak was much higher than that of the first peak. The overall sex ratio was nearly 1:1 during the study.

The emerging female and male pupae show a sex-related tendency in the timing from early July to the end of August (Fig. 2.). From July 12th to 21st, the total number of the pupae was markedly decreasing and the number of females was slightly smaller than that of the males. However, from July 21st to August 3rd, the total number of the pupae was increasing and the number of females was somewhat higher than that of males. In August, the number of females suddenly decreased in relation to the number of males.

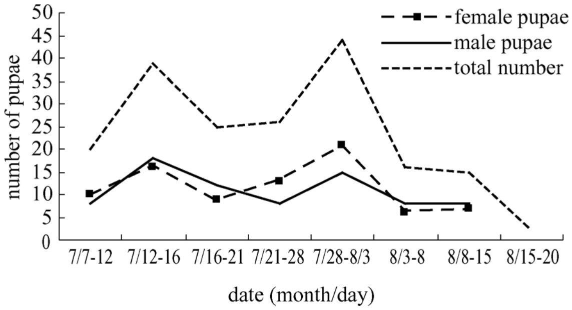


Fig. 2 Population dynamic of the *H. hippopaecolus* pupae

3.2 Distribution of the *H. hippophaecolus* pupae around the stem base

The distance from the pupae to the base of seabuckthorn stem was divided into regions with a 10 cm extending radius. The statistical number of the pupae in each region was shown in Table 1. It was found that all pupae were within a distance of 1.3 m from the base of the stem. Ninety percent of pupae were aggregated within a distance of 1 m from the base of the stem. Only one pupa (3.03%) was encountered at a distance of 1.2–1.3 m from the stem, and 11 pupae (15.15%) were encountered at a distance of both 1.0–1.1 m and 1.1–1.2 m from the stem. The distribution of the pupae was mainly defined by two factors – the length of the horizontal and vertical roots of the seabuckthorn, the distance between pupation sites and damaged root sites. The former is critical for the larvae. The mature larvae usually pupate in the soil 10 cm deep around the base of the stem and only a few larvae crawl out of the soil to pupate. Therefore, if the mature larvae are feeding on the horizontal roots far away from the base of the tree, the pupae will also be found far away from the tree base.

3.3 Spatial pattern of *H. hippophaecolus* pupae

3.3.1 Distribution of *H. hippophaecolus* pupae in forest

The statistical results show that 24.3% of the trees were found to have pupae ranging from 0 to 4 pupae per tree (Table 2).

3.3.2 Spatial variation of the pupae and grid size

It is well known that only the appropriate grid size can correctly reflect the spatial structure of a population. If the grid size is too small, the differences of data among the sample plots are big and it can entirely cover the correlation among the sample plots which is caused by the spatial position. If the grid size is too big, the differences are not significant and the value of each sample plot will form a uniform distribution. Consequently, the distance of spatial dependence will decrease and the pure nugget variogram is formed. Therefore, we had separately compared the variable parameters of the pupae with different grid sizes in order to accurately study the spatial structure to obtain an appropriate grid size. The results are shown in Figs. 3–6.

Table 1 Distribution of the *H. hippophaecolus* pupae around the stem base

distance from the base of the stem/m	0–0.1	0.1–0.2	0.2–0.3	0.3–0.4	0.4–0.5	0.5–0.6	0.6–0.7	0.7–0.8	0.8–0.9	0.9–1	1–1.1	1.1–1.2	1.2–1.3
number of pupae	24	30	14	17	27	22	10	8	6	17	11	11	1
percentage/%	12.12	15.15	7.07	8.59	13.64	11.11	5.05	4.04	3.03	8.59	5.56	5.56	0.51
total percentage/%	12.12	27.27	34.34	42.93	56.56	67.68	72.73	76.77	79.80	88.38	93.94	99.49	100

Table 2 Number of the pupae per seabuckthorn

number of the pupae	0	1	2	3	4
frequency/tree	735	202	26	7	1
percentage/%	75.70	20.80	2.68	0.72	0.10
accumulative percentage/%	75.70	96.50	99.18	99.90	100.00

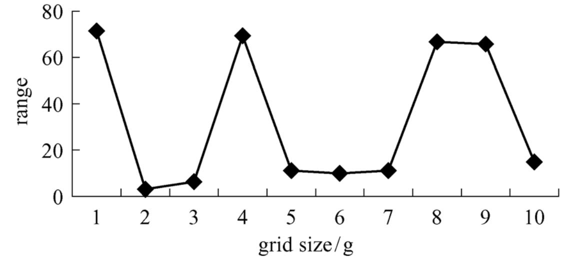


Fig. 3 Relationship between range and grid size of variogram for pupae

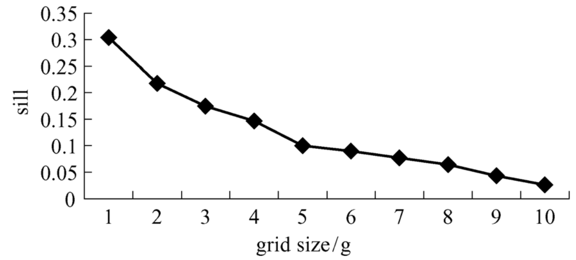


Fig. 4 Relationship between sill and grid size of variogram for pupae

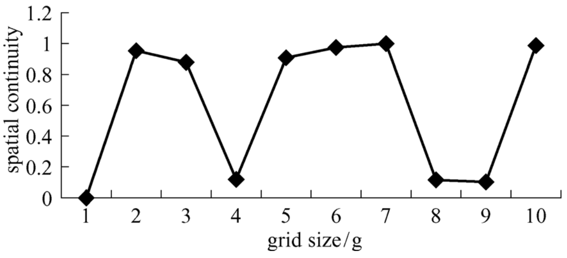


Fig. 5 Relationship between spatial continuity and grid size of variogram for pupae

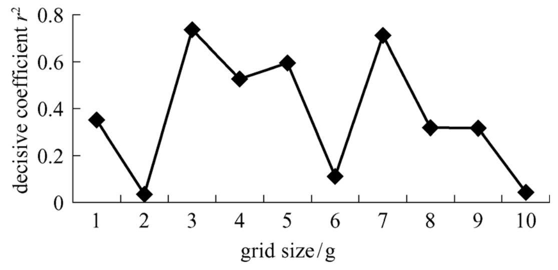


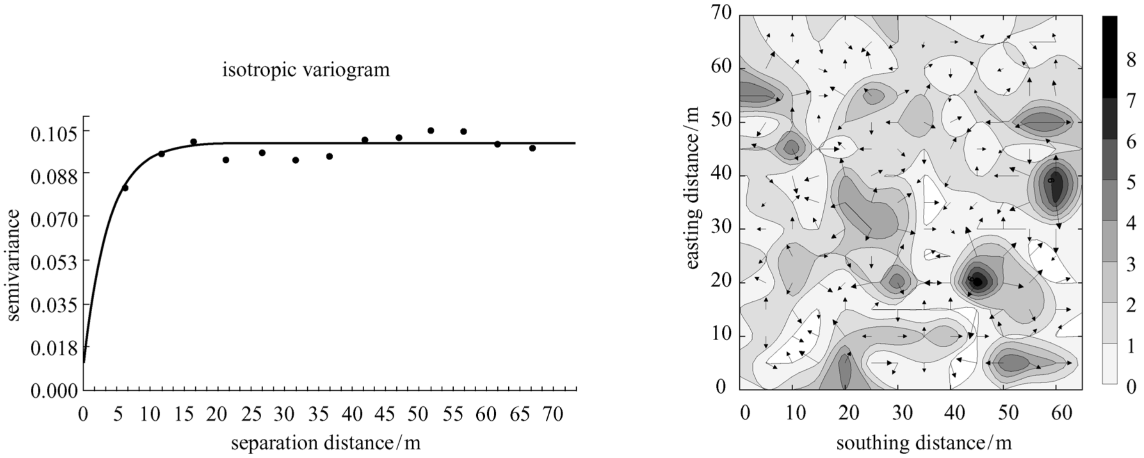
Fig. 6 Relationship between decisive coefficient and grid size of variogram for pupae

The range, the intensity of local spatial continuity and the decisive coefficient for the variogram of the pupae all show a large change along with the increasing grid size. As shown in Figs. 3, 5, 6, the extent of change and intensity of local spatial continuity were small and nearly equal to each other when the grid size was 5–7 m. However, when the grid size was either 3 m, 5 m or 7 m, the value of the decisive coefficient was relatively higher and the fit precision to the variance curve was much more significant. The trend for the sill was decreasing (Fig. 4) because the variation of internal sample plots was increasing and that among sample plots was decreasing with the increasing grid size. Yet, when the grid size was 5–7 m, the sill had a very small change range. Therefore, the range and intensity of the local spatial continuity and the decisive coefficient of the variogram for the pupae were relatively stable and little changed on the appropriate grid size. The cause of stability was the population's intrinsic factors and having nothing to do with the grid size. Considering this, we selected the grid size of 5 m × 5 m to analyze the spatial structure and change regulation of the *H. hippophaecolus* pupae.

3.3.3 Isotropic variogram and spatial pattern of the pupae

The exponential model of the fitted variogram shows the *H. hippophaecolus* pupae represented with an intense spatial aggregation in the sampled forest (Fig. 7a) and the range of the spatial dependence was 11.1 m. The number of the pupae had a correlation between any two sample spots in this range. In other words, the spatial distribution of the pupae was continuous and its intensity was decreasing with the increasing separation distance. The proportion of the height of arch (C) was 90.7% in the variogram. 90.7% of the spatial variability was caused by the spatial autocorrelation. According to the results of the observation and investigation in field, the spatial pattern of the pupae was mainly relevant to that of the larvae. The results for the larvae in the same experiment field shows that the larvae also appeared as an intense spatial aggregation and the spatial dependence of the larvae was 7.3 m (Zong et al., 2005). This figure was smaller than that of the pupae because only a small part of the mature larvae pupate. Since the number of the pupae is smaller than that of the larvae, the intensity of spatial aggregation of the pupae was clearly smaller than that of the larvae expanding the spatial dependence of the pupae.

The nugget was caused by the decreased number of the pupae due to overgrazing and chopping for firewood. This caused large numbers of the seabuckthorn to disappear, leading to further reduction in the number of larvae. Moreover, some pupae had died because of the adverse environmental conditions, such as rain. The spatial aggregation of the pupae was analyzed by the overlay map of the isoline and vector. The result indicated that the population of the pupae presented an intensive spotted distribution and many aggregated spots were found in the entire woodland. The value of each aggregated spot



(a) (b)

Fig. 7 Variogram (a) and an overlay map of isoline and vector (b) of the seabuckthorn carpenter worm pupae

gradually decreased from the central region to its surroundings. No significant difference of the pupae among grids near to the centre of the aggregated spots was detected, but the difference became larger the farther away you move from the centre.

4 Discussion

The distribution of the pupae of *H. hippophaecolus* around the base of stems is mainly defined by two factors, the length of the seabuckthorn horizontal and vertical roots and the distance between sites where the mature larvae pupate and damage the roots. Most of pupae were found aggregating within 1 m from the base of the stem. This result provides a better theoretical basis for artificially catching unmated moths. According to the biological characteristics of *H. hippophaecolus*, it is concluded that the moths do not move on the ground after emerging from the pupa. After sunset, they begin to move around 8:00 p.m. Since the moths emerge mainly around 4:00 p.m. to 6:00 p.m., theoretically, the population density of the next generation can be controlled by artificially catching the moths within 1 m from the base of the stem. However, this is very difficult to apply in practice because the seabuckthorn forest is dense and very difficult for a researcher to enter. The seabuckthorns have a strong sprouting ability and the trees have thorns on the stem. Nevertheless, the seabuckthorn is ecologically and economically a valuable tree species for which cultivation and management is important for the markets. For instance, the leaves and fruit of the seabuckthorn provide raw material for health products and drinks. Thus, the artificial catching of *H. hippophaecolus* will provide an effective approach to control the damage of this pest under this management pattern.

The spatial pattern of the pupae is mainly defined by the spatial pattern of the larvae and the sites of the mature larvae in the roots. In addition, stand types, growth status of seabuckthorns in different forests and environments among others can also affect the spatial pattern. In this study, the grid size of 5 m × 5 m is the best and the pupae show an intense spatial aggregation. In the studied woodland, it was found that the spatial dependence range for the pupae of 11.1 m was bigger than that of the larvae (7.3 m).

In the study of spatial pattern, geostatistics, as a method of statistical analysis, must be consistent with the biological characteristics of pests, or else, it will not be of any significance. In this study, using geostatistics, we analyzed the quantity and spatial position of insect populations. This analysis resolved the problem of the spatial correlation and dependence and provided an effective approach to reflect the spatial pattern of the population. With the progress in ecological research, the relationship between the change of the insect population quantity and spatial position is of interest to scientists. Therefore, exploring new methods of statistical analysis as well as developing and synthesizing analyses of spatial pattern and mutual supplement will provide a better theoretical basis for understanding the spatial structure of insect populations more accurately.

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