Correlation Analysis of *Sitophilus oryzae* (Linnaeus) Real-Time Monitoring and Insect Population Density and Its Distribution Pattern in Wheat Grain Piles

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Abstract: The traditional manual sampling method for detecting stored grain insect pests is labor-intensive and time-consuming, often yielding non-representative samples. However, to achieve more accurate monitoring, it is necessary to understand the distribution patterns of different insect pests within grain silo and their correlation with monitoring and sampling data. This study aimed to assess the population density and distribution of *Sitophilus oryzae* (rice weevil) in bulk wheat grain to predict insect dynamics effectively. Utilizing a probe trap in a wheat silo, adult insects were tracked across different population densities. The traps recorded captured pests, alongside temperature and humidity data. The correlation analysis revealed that rice weevils were active throughout the silo but less prevalent at the bottom, with the highest distribution near the upper surface. Temperature and humidity significantly influenced their activity, particularly within the 22 °C to 32 °C range. Higher population densities correlated with increased relative humidity, impacting weevil activity. Trapping data aligned with overall population density changes in the silo. This study will provide an accurate assessment of the population density of adult rice weevils in grain silos based on temperature changes in the upper part of the grain silo.

Keywords: new pest-trapping device; rice weevil; monitoring; distribution pattern; influencing factors

1. Introduction

China is the world’s largest producer and consumer of food, playing a crucial role in ensuring national food security [1]. However, postharvest losses during grain storage and transportation continue to threaten food security. China loses 35 million tonnes of grain during storage and processing each year, which is equivalent to the annual food consumption of 200 million people [1]. In addition to losses incurred during processing and transportation, a significant portion of grain is damaged and contaminated by storage pests during the period of storage [1]. Therefore, pest control has always played a critical role in China’s grain storage management.

China follows the Integrated Pest Management (IPM) strategy for harmful organisms, and insect pest density monitoring is a crucial component of the IPM system [2]. Timely detection is critical for the treatment of pest infestations and significantly reduces grain losses from pest damage. This approach prevents both losses due to pests and the wastage resulting from indiscriminate pest control, which can further pollute the environment [3,4].

The traditional method for the detection of stored grain insect pests in China is manual sampling, which is labor-intensive, time-consuming, and makes it difficult to obtain representative samples. Moreover, it primarily focuses on the surface pest population and cannot accurately show the distribution of pests throughout the grain silo. With
the developments in information technology, new real-time monitoring and trapping technologies have been developed and are being applied [5]. However, to achieve more accurate monitoring, it is necessary to understand the distribution patterns of different insect pests within grain silos and their correlation with monitoring and sampling data.

The rice weevil (*Sitophilus oryzae*) is a typical primary grain-feeding pest. While causing losses by feeding on stored grains, it also generates an amount of debris powder, which provides favorable conditions for secondary grain-feeding storage pests [6–8]. Some research has explored the behavior and activity patterns of adult rice weevils in grain silos and investigated the influence of temperature and humidity on the behavior of rice weevils [9,10], which includes a certain range of temperature preferences [11]. Temperature can significantly affect the crawling speed of adult rice weevils within grain silos. The movement speed of adult rice weevils on different surface types of grains increases significantly with rising temperatures in the range of 20 to 35°C [12,13]. However, there is no research on the distribution of rice weevils within grain silos or the methods used to monitor and sample adult insects within silos.

This study utilizes a probe trap coupled with remote sensing technology to monitor the quantity and distribution of adult rice weevils within wheat silos. It aims to investigate the distribution patterns of adult rice weevils within the silo and their relationship with relevant factors to provide scientific evidence for improving the accuracy of monitoring pests.

### 2. Materials and Methods

#### 2.1. Insect Culture

The stored grain insect that was used was the adult *Sitophilus oryzae* (Linnaeus), Beijing Tongzhou strain, obtained from the Storage and Transportation Institute, the Academy of National Food and Strategic Reserves Administration, Beijing, China. The techniques used in the insect culture and handling generally followed those described by Wink’s method for *S. oryzae* reared on wheat in a constant-temperature incubator at 30 ± 3°C and 70 ± 5% relative humidity [14].

Newly harvested wheat was obtained from Lianyungang, Jiangsu, China. The wheat sample was stored at 25 ± 2°C. The moisture content of the wheat sample was 11.2 ± 0.1%, as determined with a Graintec HE 50 electronic moisture meter (Graintec Pty Ltd., Toowoomba, QLD, Australia) and calculated from four repeat measurements.

#### 2.2. Instruments and Equipment

Probe traps based on photoelectric infrared sensors were jointly developed by Beijing University of Posts and Telecommunications and the Scientific Research Institute of the State Administration of Grain and Material Reserves (Figure 1) [15]. These traps automatically detect and record the number of captured adult insect pests, as well as recording temperature and relative humidity at the corresponding collection sports.

![Figure 1. A real-time insect trap device based on photoelectric infrared sensors, which were jointly developed by Beijing University of Posts and Telecommunications and the Scientific Research Institute of the State Administration of Grain and Material Reserves.](image-url)
A pilot experimental silo with three tonnes capacity was made of stainless steel by the Scientific Research Institute of the State Administration of Grain and Material Reserves (Figure 2a). Fifteen electronic probe traps were placed at three levels: Top (1.8 m), Middle (1.2 m), and Bottom (0.6 m) (Figure 2b). Five traps and four pest release points were located at each level (Figure 2c).

Probe traps based on photoelectric infrared sensors were jointly developed by Beijing University of Posts and Telecommunications and the Scientific Research Institute of the State Administration of Grain and Material Reserves (Figure 1) [15]. These traps automatically detect and record the number of captured adult insect pests, as well as recording temperature and relative humidity at the corresponding collection spots.

Figure 2. Three-tonne capacity experimental silo (a), a schematic diagram of the silo size (b) and trap locations (b,c). OD = Outside Diameter; T = Top; M = Middle; B = Bottom; No. 1, 2, 3, 4 and 5 represent five entrapment points. Red colored cylinders represent probe traps.

2.3. Experimental Method

2.3.1. Setting Insect Densities

Insect densities were set at three gradients: low, medium, and high, corresponding to 0.1, 1.0 and 5.0 insects/kg of wheat, respectively. The wheat inside the experimental chamber weighed 2.25 tonnes; therefore, 225, 2250 and 11,250 insect adults were introduced into the silo, respectively.

2.3.2. Artificial Infestation of Rice Weevils and Data Collection

This experiment utilized a cylindrical chamber with several manual sampling ports on the side for validation through manual sampling. Within the grain pile inside the chamber, 3 × 5 probes were buried, corresponding to the upper, middle, and lower layers of the grain pile, as well as the middle and the surrounding five positions.

Adult rice weevils were manually screened, selected, and placed in four 0.5 L glass jars with a small amount of wheat for 24 h of acclimation. Then, insects from the jars were transferred to pest placement points in the grain silo (Figure 2c). A water jacket temperature control system was used to maintain the temperature between grain kernels at 20 °C. The trap data collection, including the insect number, temperature, and humidity, was carried out continuously for 10 days. The experiments were conducted from August to December 2021 (fall to winter) and March to June 2022 (spring to summer).

To investigate the significant impact of grain pile temperature and relative humidity data on trap capture data at pest population densities of 0.1, 1.0, and 5.0 insects/kg, temperature data were first grouped into intervals of 15–20 °C, 20–25 °C, 25–30 °C, and 30–35 °C, while relative humidity data were grouped into intervals of 40–45 °C, 45–50 °C, and 50–55 °C. Subsequently, a multifactor analysis of variance (ANOVA) was used to analyze the influencing factors of trap capture data.

To understand whether the grain temperature and relative humidity have a significant impact on the trapping under insect population densities of 0.1, 1.0, and 5.0 adult insects/kg of wheat, a two-factor analysis of variance (ANOVA) was performed on the experimental data. The grain temperature and relative humidity data collected in this experiment
were the actual daily average data that were measured. During the experiment, the grain temperature and relative humidity values are different every day; therefore, these two independent variables need to be predicted and then analyzed.

2.3.3. Data Validation

After 10-day experiments, infested 1 kg wheat samples were collected from each sampling port and insect numbers were counted after screening with a 2 mm insect sieve with a catch pan for data validation. The number of rice weevils sampled at each point and the corresponding air temperature and humidity were recorded, and these data were compared with the probe monitoring data.

2.4. Data Processing and Analysis

The detection percentage of pests at different layers (Recovery Percentage at Different Layers, RPDL) within each repeat group was calculated. The definition of the RPDL was as follows:

$$RPDL = \frac{L}{T} \times 100$$

$L = \text{the total number of pests detected by the five probe traps in a particular layer}.

T = \text{the total number of pests detected by all 15 probe traps in the experimental storage.}$

To analyze the correlation between the trapping frequency (trap frequency, $T_f$), defined as the average number of captures of each trap during the trapping period, and the artificially introduced insect density, Pearson correlation coefficients were calculated between the artificially introduced insect density and the trapping frequency of each trap for trapping periods of 3, 5, 7, and 10 days.

$$T_f = \frac{\text{Total trapped adult insects during period of trapping (Adult insects)}}{\text{Period of trapping (day)}}$$

Time series graphs and Augmented Dickey–Fuller (ADF) tests were used for a time series analysis of trapping data. Multiple-factor analysis of variance was employed to study the relationship between trapping results and grain pile temperature and relative humidity. Pearson correlation coefficient analysis was used to investigate the relationship between trapping frequency and grain pile insect density and the correlation between trapping frequency at different trapping locations and grain pile insect density. The feasibility of predicting grain pile insect density based on trapping data was studied using the Support Vector Regression method. All these data analysis tasks were carried out using SPSS 29.0.0.0 and Excel 365.

For the assessment of insect density based on trap data, Support Vector Regression (SVR) was employed to assess insect density using trap data alone, trap data along with temperature data, trap data along with relative humidity data, and trap data along with temperature and relative humidity data.

3. Results

3.1. Analysis of the Temporal and Spatial Distribution Patterns of Rice Weevil Trapping Data

3.1.1. Analysis of the Temporal Continuity of Trapping Data

To understand whether there was a certain regularity in the temporal dimension of weevil trapping data, time series plots were created for the daily trapping totals for each of the 15 traps under different insect densities. Unit root tests were performed to analyze the temporal continuity of the trapping data. The time series plot is shown in Figure 3, and the test results (ADF values and $p$-values) for different insect densities are shown in Table 1.

As shown in Figure 3, rice weevils spread throughout the grain pile 24 h after being introduced from the top of the grain heap. There were noticeable differences in the fluctuations in the cumulative catch quantities in different repeat groups. Furthermore, when the insect density was 5.0 adult insects/kg, the cumulative catch quantity in repeat group 1 was significantly higher than that in the other two repeat groups. This may be because
the experiments in repeat group 1 were conducted in August and September, when the external temperatures and grain temperatures inside the warehouse were higher, resulting in an increase in the activity of adult rice weevils and, consequently, more adult rice weevils being detected by the probe traps.

![Time series chart](image)

**Figure 3.** Time series chart of the daily catch of 15 traps in three repeated experiments at 0.1 insect/kg, 1.0 insect/kg, and 5.0 insect/kg. R1, R2, and R3 represent the three repeated experiments that were conducted.
The ADF test mainly relies on the \( p \)-value for evaluation, using the standard value of 0.05 as a reference. When the \( p \)-value is less than 0.05, this indicates the rejection of the null hypothesis, meaning that there was not a unit root in the time series data of trapping. However, all \( p \)-values were greater than 0.05, indicating that, under these three pest density conditions, the total sum of captures for each repeat group was non-stationary and irregular over time (Table 1).

Table 1. Augmented Dickey–Fuller (ADF) test results. R1, R2, and R3 represent the three repeated experiments that were conducted.

<table>
<thead>
<tr>
<th>Population (Insects/kg of Wheat)</th>
<th>Replications</th>
<th>ADF</th>
<th>( p )-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>R1</td>
<td>0.00</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>R2</td>
<td>−1.73</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>R3</td>
<td>−2.65</td>
<td>0.08</td>
</tr>
<tr>
<td>1.0</td>
<td>R1</td>
<td>−0.00</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>R2</td>
<td>0.00</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>R3</td>
<td>−1.01</td>
<td>0.75</td>
</tr>
<tr>
<td>5.0</td>
<td>R1</td>
<td>−1.92</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>R2</td>
<td>0.00</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>R3</td>
<td>1.11</td>
<td>0.99</td>
</tr>
</tbody>
</table>

3.1.2. Spatial Distribution of Trapping Data

The detection percentages of pests at different layers, defined as the Recovery Percentage at Different Layers (RPDL), were calculated within each repeat group (Formula (1)). For each repeat group, RPDL for the top, middle, and bottom layers was calculated separately, and the results are presented as mean \( \pm \) standard error (SE) (Table 2). At 0.1 and 1.0 insects per kg of wheat, there was the highest average of RPDLs, 56.65% and 37.53%, respectively, at the middle level and the lowest average of RPDLs, 18.38% and 29.86%, respectively, at the bottom level of the silo. Upon increasing the population density to 5.0 insects per kg, the three layers had average RPDLs of 39.16, 30.32, and 30.52%, at the top, middle, and bottle layers.

Table 2. Statistical results of PRDL at three silo layers, top, middle, and bottom, in three repeated experiments, R1, R2, and R3.

<table>
<thead>
<tr>
<th>Population</th>
<th>Repeats</th>
<th>RPDL of Rice Weevils (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insects/kg of Wheat</td>
<td></td>
<td>Top</td>
</tr>
<tr>
<td>0.1</td>
<td>R1</td>
<td>15.38</td>
</tr>
<tr>
<td></td>
<td>R2</td>
<td>16.67</td>
</tr>
<tr>
<td></td>
<td>R3</td>
<td>42.86</td>
</tr>
<tr>
<td></td>
<td>Ave ± SE</td>
<td>24.97 ± 8.95</td>
</tr>
<tr>
<td>1.0</td>
<td>R1</td>
<td>7.79</td>
</tr>
<tr>
<td></td>
<td>R2</td>
<td>53.19</td>
</tr>
<tr>
<td></td>
<td>R3</td>
<td>36.84</td>
</tr>
<tr>
<td></td>
<td>Ave ± SE</td>
<td>32.61 ± 13.28</td>
</tr>
<tr>
<td>5.0</td>
<td>R1</td>
<td>19.36</td>
</tr>
<tr>
<td></td>
<td>R2</td>
<td>34.02</td>
</tr>
<tr>
<td></td>
<td>R3</td>
<td>64.11</td>
</tr>
<tr>
<td></td>
<td>Ave ± SE</td>
<td>39.16 ± 13.17</td>
</tr>
</tbody>
</table>

RPDL = Recovery percentage of adult insects at different layers of grain in silo; SE = standard error.

3.2. Correlation Analysis between Trap Data and Grain Stack Temperature and Humidity

Scatter plots were created to visualize the relationship between daily average rice grain temperature, relative humidity, and trap captures for each probe trap at different pest densities (Figure 4).
Under the experimental conditions, the temperature range detected by the probe was 18.96–34.22 °C, and the relative humidity range was 43.80–52.93%. The two independent variables were grouped within the above temperature and humidity range, and then a two-factor analysis of variance was used to analyze the influencing factors of the trapping data. At 0.1 insects per kg, Temp, R.H. and Temp × R.H. have a p value above 0.05, so there was no significant difference. However, when increasing the population density to 5.0 insects per kg, all three factors show a significant difference with p values of less than 0.003 (Table 3).

### Table 3. Analysis of factors influencing trap capture data based on multifactor ANOVA.

<table>
<thead>
<tr>
<th>Population (Insects/kg)</th>
<th>Factors</th>
<th>DF</th>
<th>Mean Square</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>Temp</td>
<td>3</td>
<td>0.07</td>
<td>1.13</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>R.H.</td>
<td>2</td>
<td>0.01</td>
<td>0.24</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>Temp × R.H.</td>
<td>4</td>
<td>0.01</td>
<td>0.21</td>
<td>0.97</td>
</tr>
<tr>
<td>1.0</td>
<td>Temp</td>
<td>2</td>
<td>2.78</td>
<td>6.37</td>
<td>0.002 **</td>
</tr>
<tr>
<td></td>
<td>R.H.</td>
<td>2</td>
<td>0.17</td>
<td>0.39</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>Temp × R.H.</td>
<td>4</td>
<td>1.23</td>
<td>2.81</td>
<td>0.03 *</td>
</tr>
<tr>
<td>5.0</td>
<td>Temp</td>
<td>3</td>
<td>323.67</td>
<td>46.26</td>
<td>0.000 **</td>
</tr>
<tr>
<td></td>
<td>R.H.</td>
<td>1</td>
<td>70.75</td>
<td>10.11</td>
<td>0.002 **</td>
</tr>
<tr>
<td></td>
<td>Temp × R.H.</td>
<td>3</td>
<td>58.46</td>
<td>8.35</td>
<td>0.000 **</td>
</tr>
</tbody>
</table>

* 0.05 < p < 0.01.  ** p < 0.01.

3.3. Correlation Analysis between the Location of Monitored Points and Insect Density

Based on Trap frequency, Pearson correlation coefficients were calculated between the artificially introduced insect density and the trapping frequency of each trap for trapping periods of 3, 5, 7, and 10 days, showing that the longer the trapping period, the stronger the correlation between the trapping frequency and the insect density in the grain pile (Formula (2)) (Table 4).

### Table 4. Results of Pearson correlation coefficients between the trapping frequency of each trap at different trapping periods and the insect density.

<table>
<thead>
<tr>
<th>Pearson Correlation Coefficient</th>
<th>Period of Trapping (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td>R</td>
<td>0.618 *</td>
</tr>
</tbody>
</table>

* The Pearson correlation coefficient p-values between trap frequency and insect population density < 0.05.
To investigate the relationship between trapping catch frequency and insect population density at different trapping locations, Pearson correlation coefficients were calculated for trap deployments at various positions, with a trapping period of 10 days (Table 5). The two highest Pearson correlation coefficients, 0.978 and 0.938, with \( p \) values of less than 0.01, were found on location 1 at the top level. In contrast, the lowest two Pearson correlation coefficients, 0.537 and 0.552, were found on location 3 at the middle and bottom levels.

### Table 5. Pearson correlation coefficients between insect population density and trap catch frequency at different trap locations (trapping period of 10 days).

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Location</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>0.978 **</td>
<td>0.938 **</td>
<td>0.309</td>
<td>0.790 *</td>
<td>0.704 *</td>
<td></td>
</tr>
<tr>
<td>Middle</td>
<td>0.782 *</td>
<td>0.583</td>
<td>0.537</td>
<td>0.698 *</td>
<td>0.685 *</td>
<td></td>
</tr>
<tr>
<td>Bottom</td>
<td>0.709 *</td>
<td>0.732 *</td>
<td>0.552</td>
<td>0.638</td>
<td>0.571</td>
<td></td>
</tr>
</tbody>
</table>

* and ** represent Pearson correlation coefficient \( p \)-values of less than 0.05 and 0.01, respectively, for the correlation between insect density and trap frequency.

### 3.4. The Details of Specific Implementation

The daily capture count, daily average grain temperature, and daily average relative humidity data collected by each trap were each treated as a basic data unit. Within a 10-day trapping period, a baited probe trap generated 10 basic data units. These 10 basic data units comprised one data sample.

Each baited probe trap produced one data sample for each insect density, and since there were 15 baited probe traps operating simultaneously in each density level within each repeat group, there were 15 data samples for each insect density level. As the data collection experiments were conducted in three storage bins, the dataset consisted of 135 data samples, with 45 samples for each pest occurrence level. Before training, Z-score standardization was applied to preprocess the data for trap count, grain temperature, and relative humidity.

Due to the limited number of samples (135 in total), the experimental results were validated through K-fold cross-validation (K = 5). The training and testing samples were entirely independent, and the hyperparameter settings for this K-fold cross-validation were consistent. The experimental results were presented as the average of the K-fold cross-validation results.

The results of the assessment of insect density are based on trap data, trap data along with temperature data, trap data along with relative humidity data, and trap data along with temperature and relative humidity data. The combination of Trap + Temperature had the lowest MSE and MAE, at 1.68 and 0.82 (Table 6).

### Table 6. The K-fold cross-validation of insect density assessment.

<table>
<thead>
<tr>
<th>Different Data Combinations</th>
<th>MSE a</th>
<th>MAE b</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trap</td>
<td>2.21</td>
<td>0.87</td>
<td>0.50</td>
</tr>
<tr>
<td>Trap + Temperature</td>
<td>1.68</td>
<td>0.82</td>
<td>0.62</td>
</tr>
<tr>
<td>Trap + Relative Humidity</td>
<td>2.46</td>
<td>1.03</td>
<td>0.44</td>
</tr>
<tr>
<td>Trap + Temperature + Relative Humidity</td>
<td>2.02</td>
<td>0.95</td>
<td>0.54</td>
</tr>
</tbody>
</table>

a MSE (Mean Square Error): The expected value of the square of the difference between the predicted value and the actual value. The smaller the value, the higher the accuracy of the model. b MAE (Mean Absolute Error): The average value of the absolute error can reflect the actual situation of the predicted value error. The smaller the value, the higher the accuracy of the model.

### 4. Discussion

#### 4.1. Spatial Distribution of Trapping Data

Insects were distributed throughout the upper, middle, and lower layers, with a higher likelihood of detection in the upper and middle layers. This may be because insects in
the upper and middle layers of the grain have more contact with the air and relatively higher temperatures, which align with the rice weevil’s thermophilic behavior. Moreover, observations during the rearing process indicate that rice weevils tend to move towards the upper end of the container.

Studies have shown that several grain storage pests exhibit a noticeable vertical distribution within bulk grain, rather than being concentrated on the surface or upper layers [16–18]. However, over 80% of rice weevils were reported to be aggregated at the top in bulk grain, which differs from the results of this experiment [19].

4.2. Correlation Analysis between Trap Data and Grain Stack Temperature and Humidity

The effects of temperature and relative humidity on the trapping results of adult rice weevils in grain were not significant, at 0.1 insect head per kilogram (Table 3). However, as the insect density increased, the impact of temperature on the trapping results became significant, and when the insect density further increased to 5.0 insects/kg of wheat, both temperature, relative humidity, and their interaction had significant effects on the trapping results. When the temperature was above 10 °C, the increasing temperature accelerated the flat movement of rice weevils, and their movement rate on grain surfaces was significantly lower than on non-grain surfaces at between 22 and 31 °C [20]. Rice weevils were found to exhibit significant thermotaxis in temperature gradients of 20–30 °C and 20–35 °C in grain; after cooling, rice weevils tended to migrate to the warmer center of the grain pile [21]. This study once again confirms that grain pile temperature and humidity have a certain degree of influence on pest activity and distribution. Also, the rust-red flat grain beetle moved faster in low-moisture grains than in medium- and high-moisture grains [22–24]. This study did not measure grain moisture, and the results of this study also provide new directions for this research topic.

4.3. Correlation Analysis between the Location of Monitored Points and Insect Density

There were 15 traps at three levels of three repeated experiments due to the seasonal differences in external temperature and grain humiture in the lab warehouse, resulting in significantly different activity levels of rice weevil adults and reflecting the detection data of the probe trap. In the vertical direction, there was a higher correlation between trap data from the top layer and insect population density, whereas in the horizontal direction, trap data from the central location exhibited a higher correlation with insect population density. The activities of rice weevils were found to be significantly affected by temperature [20,21]. Therefore, the temperature variation among the 15 different locations may play an important role in the correlation between the location of monitored points and insect density. The correlation was also validated in Section 3.4. In addition, when the external temperature is higher, it may affect the detection accuracy of the electronic probe trap and have an impact on the data.

4.4. The Details of Specific Implementation

For bulk wheat, accuracy of the assessment of insect density was higher when trap data were combined with temperature data (Table 6). This aligns with the results of the presented trap data influence analysis (Table 3). However, the inclusion of relative humidity data reduced the accuracy of insect density assessments, which validated the humidity effects on stored grain insects’ behaviors [22–24]. This may be attributed to the greater sensitivity of the insects to temperature gradients within the bulk grain, while changes in relative humidity within the bulk grain have a minimal impact on behavior. Additionally, fluctuations in relative humidity within the bulk grain may be more related to heat and mass transfer phenomena occurring within the bulk grain and have a lower correlation with adult wheat weevil activity or respiration behavior. Therefore, when assessing grain insect density based on trap data, combining these data with grain temperature can improve the accuracy of insect density assessments.
5. Conclusions

This study utilized a real-time insect monitoring system to track the activity, distribution, influencing factors, and correlation between monitoring quantity and insect density of adult wheat weevils at different density levels in a 3-tonne wheat grain silo, and the following outcomes were achieved:

Firstly, in terms of spatial and temporal distribution, adult wheat weevils exhibited activity in both the upper, middle, and lower parts of the silo, with relatively fewer occurrences at the lower part and the highest occurrence at the upper part. Over the 10-day observation period, there were no significant daily variations in the collected data.

Secondly, relative humidity and temperature within the bulk grain had an influence on the activity of adult wheat weevils, with temperature having a more pronounced effect. Relative humidity had an impact on adult wheat weevil activity, which was particularly evident at higher insect density levels.

Thirdly, the trap data of adult wheat weevils could reflect changes in the overall insect density within the grain. Collecting data from the upper part of the grain and combining them with grain temperature data provided a more accurate assessment of insect density within the bulk grain.

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References
3. Vick, K.W.; Webb, J.C.; Weaver, B.A.; Litzkow, C. Sound detection of stored product insects that feed inside kernels of grain. J. Econ. Entomol. 1988, 81, 1489–1493. [CrossRef]


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