

Research Article

Spatial dispersion and optimum sample size for Bird cherry-oat aphid, *Rhopalosiphum padi* (Hemiptera, Aphididae) on corn

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Abstract: The bird cherry-oat aphid, *Rhopalosiphum padi* L. (Hemiptera: Aphididae), is one of the most important biotic constraints for corn production. Significant yield loss can occur without pest monitoring and timely management. Understanding the spatial distribution of *R. padi* is critical to developing a reliable sampling plan. This study aims to characterize the spatial distribution of aphids in corn fields in Karaj (Alborz province, Iran). Field sampling of *R. padi* populations (nymphs and adults) on corn in Karaj in September 2022 produced a dataset of 20 estimates of mean aphid density (m ; number of aphids per plant) and variance (s^2). To determine its distribution and inform population density sampling, we investigated the spatial distribution of *R. padi* using Taylor's power law and Iwao's mean crowding. Both methods indicated an aggregated distribution, as the aggregation parameter ($b = 1.379$) and density contagiousness coefficient ($\beta = 3.577$) exceeded 1. We then estimated the optimal sample size (n) at 0.10 and 0.25 precision levels using both models. Optimal sample size decreased with decreased precision and mean aphid density, varying significantly with both the precision level and regression model. At a 25% precision level, the required sample size ranged from 56 to 516 plants (Taylor's) and from 59 to 802 plants (Iwao's). When precision is increased to 10%, the required sample sizes become 334–3,227 plants (Taylor's method) and 371–5,013 plants (Iwao's method). These data on spatial distribution and optimal sample size are crucial for monitoring and managing *R. padi* effectively.

Keywords: *Rhopalosiphum padi*, Taylor's power law, Iwao's mean crowding, optimum sample size

Introduction

The bird cherry-oat aphid, *Rhopalosiphum padi* (L.) (Hemiptera, Aphididae), is an important pest of cereal crops such as oats, wheat, barley, and corn (Blackman and Eastop, 2000). Severe infestation of this aphid can cause serious yield

losses of cereals through feeding damage, tassel cover by honeydew (Everly, 1960; Foott and Timmins, 1973; Kieckhefer and Kantack, 1980, 1986; Bing *et al.*, 1991), and viral infection (Blackman and Eastop, 2000; Van Emden and Harrington, 2007). It is distributed worldwide, including Korea, Japan, New Zealand,

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Southeast Asia, India, Europe, Russia, North America, and Hawaii (Blackman and Eastop, 2000; Kim, 2008). In Iran, this pest infests wheat, barley, and corn nationwide (Rezvani, 2001), but its economic impact remains unclear because accurately assessing pest density is difficult.

The abundance of the aphid *R. padi*, a common corn pest, varies considerably by year and location. Understanding its dispersal patterns is crucial for comprehending its population dynamics. Arthropod distribution can be modeled using theoretical probability distributions, with empirical relationships derived through regressions of Lloyd's mean crowding against sample mean parameters (Iwao, 1968) and variance-mean relationships using log-linear regression (Taylor, 1961, 1984). Factors such as temperature, relative humidity, and host plant quality influence aphid spatial distribution (Mann *et al.*, 1995; Elliott and Kieckhefer, 2000). Effective pest management relies on appropriate sampling approaches to gather information on pest distribution and economic damage, which is crucial for establishing sampling strategies (Stern, 1959; Binns and Nyrop, 1992). Aphids frequently disperse due to the parthenogenetic production of numerous winged forms (Taylor, 1984; Simon *et al.*, 2002). Determining pest spatial distribution is crucial for effective management. While *R. padi* dispersion has been studied in wheat (Ekbom, 1985; Ward *et al.*, 1985; Elliott and Kieckhefer, 1986; Boeve and Weiss, 1998; Klueken *et al.*, 2008; Bakry *et al.*, 2020; Alawi *et al.*, 2021; Sun *et al.*, 2025), its distribution in corn remains unknown.

This study characterizes the spatial distribution of *R. padi* in corn fields, determines the optimal sample size for estimating population densities with predefined precision, fills a gap in ecological knowledge, and informs future sampling strategies.

Materials and Methods

Field study In September 2022, aphid populations were studied weekly in five

commercial cornfields (Var. SC403su) in Karaj, Alborz province, Iran, by randomly selecting and counting aphids on 100 plants per field. The number of aphids on each plant was recorded for each field and date separately. Aphid populations were recorded for four consecutive weeks, a period when they are at their highest in Karaj province (unpublished data). The mean and variance were calculated for each field and sampling occasion.

Analysis of the spatial distribution. The spatial distribution of *R. padi* in cornfields was analyzed and described using Taylor's power law (TPL) (Taylor, 1961) and Iwao's mean crowding (Iwao, 1968) methods.

Taylor's power law: Taylor's power law (Taylor, 1961) states that a population's variance (s^2) is proportional to a power of its mean ($\bar{x}$), expressed as $s^2 = \alpha \bar{x}^b$, where α and b are parameters estimated through regression analysis.

$$\ln(s^2) = \ln(\alpha) + b \ln(\bar{x})$$

According to Taylor (1961) and Taylor *et al.*, (1978), a regression coefficient (b) of 1 indicates random distribution, < 1 regular distribution, and > 1 aggregated distribution.

Iwao's mean crowding: Iwao's mean crowding regression (Iwao, 1968) was used to determine the relationship between mean density ($\bar{x}$) and mean crowding index ($x^* = \bar{x} + \left(\frac{s^2}{\bar{x}}\right) - 1$), (Lloyd 1967) expressed as $x^* = \alpha + \beta \bar{x}$. A positive α indicates attraction, while a negative α indicates repulsion between individuals. The β value, analogous to Taylor's power law b value, indicates spatial distribution: $\beta = 1$ for random, $\beta < 1$ for regular, and $\beta > 1$ for aggregated distribution.

We evaluated the fit of two regression models for explaining the spatial pattern of *R. padi* by comparing their coefficients of determination (r^2). The randomness of the dispersion was tested using a Student's *t*-test, with the null hypothesis that the regression

slope was equal 1. The test statistics were calculated as $t = (b-1)/s_b$ and $t = (\beta - 1)/s_\beta$, where s_b and s_β represent the standard errors of the regression slopes for each model. These calculated t-values were compared to the two-tailed critical t-value with $n-2$ degrees of freedom.

Optimum number of sample units (sample size)

The optimal number of sample units is the minimum needed to satisfy the sampling program's objectives and achieve the desired precision of estimates. Karandinos (1976) provided a general formula for calculating the optimal numerical sample size as:

$$n = \left[\frac{Z_{\alpha/2}}{D} \right]^2 \frac{s^2}{\bar{x}^2}$$

where $Z_{\alpha/2}$ is the upper $\alpha/2$ point of the standard normal distribution, and D is the desired half-width of the confidence interval (CI), expressed as a decimal. Karandinos (1976) defined the CI as a percentage of the parameter D , where $1/2 CI = D\bar{x}$ or $D = CI/2\bar{x}$.

Taylor's power law (Taylor, 1961) and Iwao's mean crowding regression (Iwao, 1968) were used to determine the optimum sample size. The general formula for optimum sample size proposed by Karandinos (1976) was adapted using parameters from these two methods. This was achieved by substituting the variance s^2 in Karandinos' formula with the variance estimates from Taylor's law $s^2 = a\bar{x}^b$ and Iwao's mean crowding regression $s^2 = (\alpha + 1)\bar{x} + (\beta - 1)\bar{x}^2$, respectively. This substitution yielded the following method-specific formulae for optimum sample size:

Based on Taylor's power law:

$$n = \left(\frac{Z_{\alpha/2}}{D} \right)^2 (\alpha \bar{x}^{b-2})$$

Based on Iwao's mean crowding:

$$n = \left(\frac{Z_{\alpha/2}}{D} \right)^2 \left(\frac{\alpha + 1}{\bar{x}} + (\beta - 1) \right)$$

Results

The complete dataset included mean and variance estimates from 20 *R. padi* samples collected from five fields in September 2022. The mean density of *R. padi* in the samples ranged from 0.18 to 6.92 aphids per plant. These 20 data sets for *R. padi* were used for the dispersion analysis.

Measures of aggregation

The results of Taylor's power law and Iwao's mean crowding regression of m^* on m analysis are listed in Table 1. The relationship between variance and mean density for *R. padi* was well described by Taylor's power law (Table 1; Fig. 1a). An aggregated distribution was indicated, as the intercept was significantly greater than zero ($P < 0.0001$) and the slope was significantly greater than one ($P < 0.05$). Similarly, Iwao's mean crowding regression revealed a significant relationship between mean crowding and density (Table 1; Fig. 1b). A positive intercept ($P < 0.0001$) suggests that individuals of *R. padi* form the basic component of the population, while a slope significantly greater than one ($P < 0.05$) further confirms an aggregated distribution (Table 1).

Table 1 Taylor's power law and Iwao's patchiness regression statistics for *R. padi* in cornfield and test for differences of slopes from unit.

Method	n	Parameters estimations						Test for slope $\neq 1$		
		Intercept $\pm$ SE	Slope $\pm$ SE	r^2	F	df	P	MSE [§]	$t = (\text{slope} - 1)/\text{SE}_{\text{slope}}$	P
Taylor's power law	20	11.586 $\pm$ 1.059*	1.379 $\pm$ 0.046	0.981	8631	19	< 0.0001	0.044	8.263	< 0.05
Iwao's regression method	20	0.932 $\pm$ 1.753	3.577 $\pm$ 0.486	0.76	905.203	19	< 0.0001	18.563	5.366	< 0.05

* antilogarithm of $\ln a$ from regression analysis.

§ mean square error.

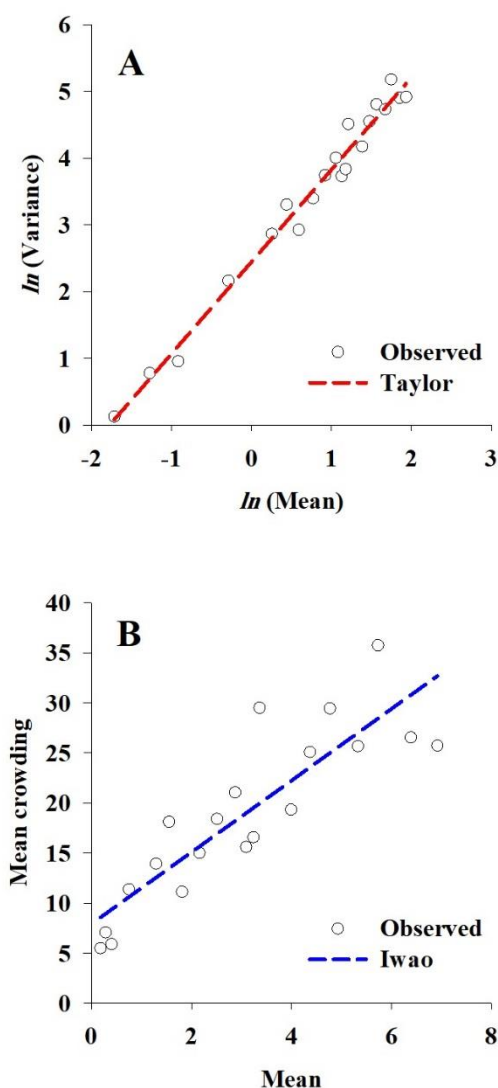


Figure 1 Linear regression of $\ln$ variance on $\ln$ mean (A) and mean crowding on mean (B) on corn plant.

Taylor's power law fit the observed data better than Iwao's mean crowding regression model, as indicated by a higher coefficient of determination ($r^2 = 0.981$ vs. 0.76 ; Fig. 1a, 1b). In both models, the aggregation index (slop) was significantly greater than one, confirming an aggregated distribution of *R. padi* on corn. Figure 2 displays the variance calculated using the mean and parameters in Table 1, along with variances from Taylor's Power Law and Iwao's mean crowding regression analysis. In general, variance increased with aphid density (Fig. 2).

Optimal sample sizes

Figure 3 shows the optimal sample size curves for *R. padi* for Taylor's power law and Iwao's mean crowding regression at two precision levels, defined as the standard error relative to the mean (SE/m). The curves correspond to SE/m ratios of 10% and 25% (where $D = 0.2$ and 0.5 , respectively), representing a range of accuracy requirements for field studies. For both models, the optimal sample size (n) was inversely related to the mean *R. padi* population. The optimal sample size (n) depends on population density and precision level. The optimal sample size for *R. padi* varied significantly with the precision level and the regression model used (Fig. 3). At a 25% precision level common in pest management, the required sample size ranged from 56 to 516 plants using Taylor's coefficient and from 59 to 802 plants using Iwao's. When precision is increased to 10% (a level common in population ecology), the required sample sizes become 334–3,227 plants (Taylor's method) and 371–5,013 plants (Iwao's method).

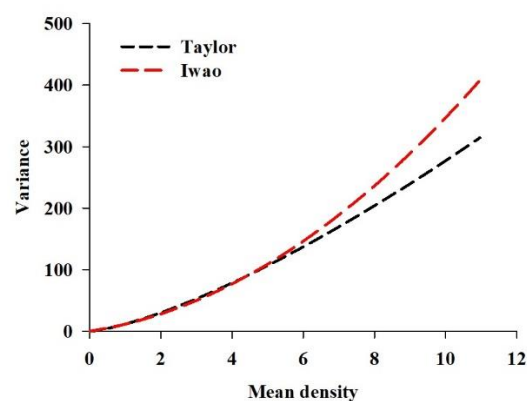


Figure 2 Predicted variance estimates versus mean density, comparing Taylor's Power Law (dashed line) and Iwao's regression (solid line).

Discussion

A species' spatial distribution is a key ecological characteristic that helps differentiate species (Chander, 1991) and is essential for developing effective sampling plans (Hassell and May,

1974; Anderson, 1974; Taylor, 1984). This understanding is crucial for precision agriculture, which can improve yields, lower costs, and conserve habitats (Weisz *et al.*, 1996; Midgarden *et al.*, 1997; Park and Tollefson, 2006). Because insect behavior is influenced by habitat interactions (Taylor, 1961), analyzing spatial distribution patterns clarifies population dynamics (Sevacherian and Stern, 1972). Distribution patterns can vary across or within habitats due to biological factors (Kuno, 1963).

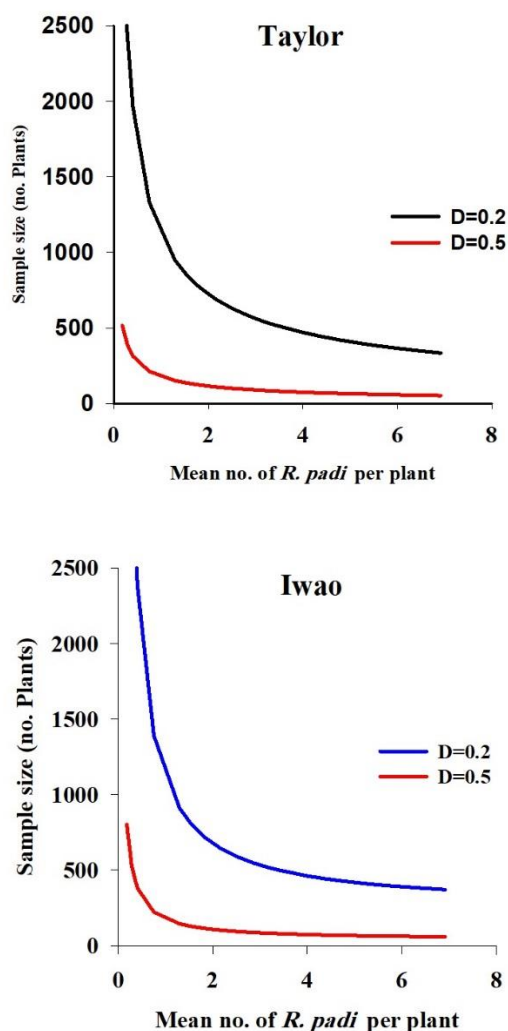


Figure 3 Optimal sample size curves for *R. padi* based on Taylor's power law and Iwao's regression ($D = 0.2$ and 0.5 ; $\alpha = 0.05$).

Our results corroborate previous findings of aggregated *R. padi* distribution in wheat (Ekbohm, 1985; Ward *et al.*, 1985; Elliott and Kieckhefer, 1986; Boeve and Weiss, 1998; Klueken *et al.*, 2008; Bakry *et al.*, 2020; Alawi *et al.*, 2021; Sun *et al.*, 2025). This aligns with documented aggregated distributions of other cereal aphids, such as *Sitobion avenae* (Fabricius), *Diuraphis noxia* (Kurdjumov), *Metopolophium dirhoclum* (Walker), and *Schizaphis graminum* (Rondani) (Tomanovic *et al.*, 2008; Borges *et al.*, 2006). While some studies reported random distribution of *S. graminum* in wheat (Kieckhefer, 1975; Ba-Angood and Stewart, 1980), others observed aggregated distribution, even across different wheat cultivars (Bakry and Shakal 2020) or in mixed aphid populations (Alawi *et al.*, 2021). Studies in Iran have also shown similar distribution patterns for *R. maidis* in broomcorn (Khodabandeh and Khaneghah, 2018) and barley (Shahrokhi Khaneghah *et al.*, 2019).

In this study, the high coefficient of determination (r^2) in Taylor's power law indicates a strong relationship between population variance and mean, where increased mean density leads to increased variance (Fig. 2). Regression analyses, as employed here, have been successfully used for various aphid species and other insect pests (Tomanovic *et al.*, 2008; Nematollahi *et al.*, 2014; Khodabandeh and Khaneghah, 2018; Alawi *et al.*, 2021).

The consistent superiority of Taylor's power law over Iwao's mean crowding regression in describing variance-to-mean relationships in ecological populations is supported by both empirical evidence and theoretical considerations. Our findings, which demonstrate a smaller mean squared error (MSE) for TPL when fitted to twenty distinct datasets, align with a substantial body of literature. Most notably, Taylor *et al.* (1978), in a comprehensive analysis of 156 datasets across a wide range of taxa, showed that TPL provides a more robust and universally applicable fit. The strength of TPL lies in its empirical foundation and simplicity; it describes a consistent, exponential relationship between variance and mean that emerges as a

fundamental pattern in nature, often attributed to the intrinsic contagion of biological populations (Kendal, 2004; Eisler *et al.*, 2008).

In contrast, Iwao's model, while developed to incorporate more specific population parameters such as the mean crowding index and the index of basic contagion, has significant theoretical limitations that can restrict its utility. As Taylor *et al.* (1979) and later Taylor (1984) note, Iwao's method can be statistically less stable, and its parameters are often biologically difficult to interpret. The model's underlying assumption that the relationship between mean crowding and the mean is linear across all densities has been repeatedly challenged, as it often fails for species with specific or complex spatial behaviors (Perry, 1981). This theoretical inflexibility makes it particularly less suitable for modeling the dispersion dynamics of a species like *R. padi* (the bird cherry-oat aphid), whose populations can exhibit a wide range of aggregation patterns in response to environmental and biotic factors. Therefore, for both predictive accuracy in statistical modeling and for a more universally reliable description of population aggregation, Taylor's power law is the more prudent and powerful tool for analyzing the variance-mean relationships of *R. padi* and other similarly distributed taxa.

Estimating the optimum sample size is crucial for efficient pest monitoring (Ward *et al.*, 1985). Our study determined the sample size (*n*) needed for *R. padi* at 10% and 25% precision levels. The minimum required sample size decreased as the mean population density of *R. padi* increased (an inverse relationship) at both precision levels, consistent with previous findings (Ekbom, 1985; Ward *et al.*, 1985). This inverse relationship between optimum sample size and mean population density has been observed in aphids (Ekbom, 1985; Ward *et al.*, 1985; Borges *et al.*, 2006; Tomanovic *et al.*, 2008; Khodabandeh and Khaneghah, 2018; Shahrokhi Khaneghah *et al.*, 2019) and other insect pests (Khaing *et al.*, 2002; Borges *et al.*, 2006; Bakry and Abdel-Baky, 2020). Examining the spatial distribution pattern and optimum sample size for monitoring the white mango

scale insect, *Aulacaspis tubercularis* (Newstead) (Hemiptera: Diaspididae) on certain mango cultivars. For a given density, a more aggregated population requires a larger sample size (Wipfli *et al.*, 1992). We chose different precision levels because ecological and behavioral studies demand high precision (10%), while IPM programs can tolerate 25% precision (Henderson and Southwood, 2016). Successful management of *R. padi* relies on a practical sampling plan, as precision and cost-effectiveness are key considerations (Pedigo and Buntin, 1994). Spatial distribution informs sampling programs and insect population forecasting (Vinatier *et al.*, 2011; Henderson and Southwood, 2016); therefore, *R. padi*'s spatial distribution parameters are useful for estimating population density and monitoring. Sample size determination should account for the population's spatial distribution pattern.

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Data Availability Statement

All data supporting the findings of this study are available within the paper.

Ethics approval

Insects were used in this study. All applicable international, national, and institutional guidelines for the care and use of animals were followed. This article does not contain any studies with human participants performed by the author.

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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پراکندگی مکانی و اندازه بهینه نمونه برای شته *Rhopalosiphum padi* (L.) (Hemiptera, Aphididae) روی ذرت

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چکیده: شته (*Rhopalosiphum padi* L.; Hemiptera: Aphididae) یکی از مهم‌ترین

عوامل محدودکننده زیستی در تولید ذرت است. در صورت عدم پایش آفت و مدیریت به موقع، ممکن است کاهش قابل توجهی در عملکرد محصول رخ دهد. درک الگوی توزیع مکانی *R. padi* برای تدوین یک برنامه نمونه برداری قابل اعتماد، از اهمیت به سزایی برخوردار است. مطالعه حاضر با هدف تعیین ویژگی‌های توزیع مکانی این شته در مزارع ذرت کرج (استان البرز، ایران) انجام شد. نمونه برداری از جمعیت‌های (پوره و بالغ) *R. padi* روی ذرت در کرج (سپتامبر ۲۰۲۲)، مجموعه داده‌ای شامل ۲۰ تخمین از میانگین تراکم شته (m = میانگین تعداد شته در هر گیاه) و واریانس (s^2) را فراهم کرد. برای تعیین نوع توزیع مکانی *R. padi* از دو روش، قانون نمایی تایلور (Taylor's power law) و روش رگرسیونی ایوانو استفاده شد. در هر دو روش مقدار $b = 1/379$ (قانون نمایی تیلور) و $\beta = 3/577$ بیش از یک بودند که نشان‌دهنده توزیع تجمع می‌باشد. سپس، اندازه بهینه نمونه (n) در سطوح دقت ۰/۱ و ۰/۲۵ با استفاده از پارامترهای هر دو مدل برآورد شد. اندازه بهینه نمونه با کاهش دقت و میانگین تراکم شته، کاهش یافت و بسته به سطح دقت و مدل رگرسیونی، تغییرات معناداری نشان داد. در سطح دقت ۲۵ درصد، اندازه نمونه مورد نیاز بین ۵۶ تا ۵۱۶ بوته (روش تیلور) و ۵۹ تا ۸۰۲ بوته (روش ایوانو) متغیر بود. با افزایش دقت به ۱۰ درصد، اندازه نمونه مورد نیاز به ۳۳۴ تا ۳۲۲۷ بوته (روش تیلور) و ۳۷۱ تا ۵۰۱۳ بوته (روش ایوانو) رسید. این اطلاعات در مورد توزیع مکانی و اندازه بهینه نمونه، برای پایش و مدیریت مؤثر *R. padi* بسیار حائز اهمیت است.

واژگان کلیدی: شته *Rhopalosiphum padi*، روش نمایی تایلور، روش ایوانو، اندازه بهینه نمونه