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MODEL APPLICABILITY TO PREDICT GROWTH RATES OF INSECTS THROUGHOUT THE STORAGE OF CORN (*ZEA MAYS* L.) GRAIN

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ABSTRACT

Insect pest infestation in stored grains can cause several losses during storage, in addition to promoting the spread of fungi, changing the temperature of the grain mass, and reducing the value of the final product. Knowing the behavior of these insect pests and how they reproduce in the grain mass is essential to design more efficient control strategies and ensure a quality final product. Thus, this work aimed to accomplish modeling and simulation of the population growth of insects *Rhyzopertha dominica*, *Sitophilus oryzae, Oryzaephilus surinamensis* and *Tribolium castaneum* throughout the storage of corn grain, using data retrieved from digital sensors of temperature installed in three Brazilian storage facilities in different regions. Data were collected through managing system CERES (company Procer Automação e Sistemas) and retrieved from 1st of July to 29th September 2019. In each one of the facilities, a silo equipped with the aforementioned sensors was used. Mean weekly values of temperature of the grain mass and the intergranular relative humidity were used, calculated using the Modified Henderson equation. The silos evaluated in facilities 1, 2, and 3 have a static capacity of 2,100; 6,304, and 93 tones, respectively, considering soybean with a bulk density of 750 kg m^{-3}. Higher growth rates of all assessed species were observed for the storage facility number 2; and lowest values for storage facility number 1. Storage facilities that presented a higher potential for the growth rate of insects are subjected to elevated levels of insect populations throughout time.

Palavras-chave:
Sensores digitais
Modelagem matemática
Monitoramento populacional
Termometria

APLICABILIDADE DO MODELO PARA PREDIZER TAXAS DE CRESCIMENTO DE INSETOS AO LONGO DO ARMAZENAMENTO DE GRÃOS DE MILHO (ZEA MAYS L.)

RESUMO

A infestação de insetos-praga em grãos armazenados pode causar diversas perdas durante o armazenamento, além de promover a disseminação de fungos, alterar a temperatura da massa de grãos e reduzir o valor do produto final. Conhecer o comportamento desses insetos-praga e como eles se reproduzem na massa de grãos é essencial para traçar estratégias de controle mais eficientes e garantir um produto final de qualidade. Assim, este trabalho teve como objetivo realizar a modelagem e simulação do crescimento populacional dos insetos *Rhyzopertha dominica*, *Sitophilus oryzae*, *Oryzaephilus surinamensis* e *Tribolium castaneum* ao longo do armazenamento de grãos de milho, utilizando dados recuperados de sensores digitais de temperatura instalados em três armazéns brasileiros em diferentes regiões. Os dados foram recolhidos através do sistema de gestão CERES (empresa Procer Automação e Sistemas) e recuperados de 1 de julho a 29 de setembro de 2019. Em cada uma das instalações foi utilizado um silo equipado com os sensores supracitados. Foram utilizados valores médios semanais de temperatura da massa de grãos e umidade relativa intergranular, calculados pela equação de Henderson Modificada. Os silos avaliados nas instalações 1, 2 e 3 têm capacidade estática de 2.100; 6.304 e 93 toneladas, respectivamente, considerando soja com densidade aparente de 750 kg m^{-3}. Maiores taxas de crescimento de todas as espécies avaliadas foram observadas para o armazém número 2; e valores mais baixos para o armazém número 1. Os armazéns que apresentaram maior potencial para a taxa de crescimento de insetos estão sujeitos a níveis elevados de populações de insetos ao longo do tempo.

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INTRODUCTION

The grain storage sector in Brazil is subjected to occasional losses caused by the insect-plague infestation, which have impacts on weight loss, fungi dissemination, waste deposition in grain mass, heat spots during storage and a consequently decrease in the nutritional and commercial values of grain (PEIXOTO *et al*., 2015; JAYAKUMAR *et al*., 2017). During storage, an ecosystem is established, subjected to transformation and deterioration caused by the interactions among physical, chemical, and biological phenomena. Factors such as temperature, air relative humidity, oxygen availability, impurity, microorganisms, insects-plague, rodents, and birds influence this ecosystem. At this stage, the loss is mostly caused by biological factors. Thus, to maintain grain quality, processes of cleaning, drying, storage, and integrated pest management must be conducted efficiently as they contribute to the final quality of grain.

Most insects-plague at grain storage is subtropical and tropical originated, requiring temperatures within the range of 27-34ºC for its complete development. However, this development can be slowed or paralyzed if the temperature is stable under 16ºC. Grain temperature reduction promotes slower biochemical and metabolic reactions in insects (AGUIAR *et al*., 2012).

In Brazil, the main primary insect-plague of storage grain are *Rhyzopertha dominica*, *Sitophilus oryzae,* and *Sitophilus zeamais,* and, among secondary insect-plague, the following species are highlighted: *Oryzaephilus surinamensis* and *Tribolium castaneum* (SARWAR, 2015; SILVA *et al*., 2017). The control of insects-plague requires an integrated approach that involves several methods, such as chemical intervention, sanitation, refrigeration, and physical and biological control, which depends on available resources. Several studies in the literature indicate that insect-plague species in stored grain developed tolerance to several insecticides (WALTER *et al*., 2016; BATTA & KAVALLIERATOS, 2018; SCHLIPALIUS *et al*., 2018). Physical control involves the use of technologies such as drying, aeration, and cooling, in order to establish at the storage ecosystem, the unfavorable conditions for the growth of insects-plague and fungi (SHARMA *et al*., 2015; FERREIRA *et al.,* 2017).

To control the temperature, the aeration systems employ thermometry systems, which are constituted by a sensor network, symmetrically disposed throughout the grain mass. Technological advances regarding wireless communication and process automation, using microprocessors, actuators, and digital sensors, provide improvement tools for monitoring and managing the storage ecosystem (LOPES *et al*., 2010; KHATCHATOURIAN *et al*., 2017; BINELO *et al*., 2019).

The study of the population growth dynamic of insects-plague aims to elucidate how and why the population density is altered over time and space. At the storage ecosystem, the systems can be studied in different ways, such as direct interventions at routines, modeling, prototypes use, mathematical modeling, analytical and simulation solutions (WIEST *et al*., 2021). Computational modeling and simulation are effective and flexible tools in predictive analysis because they provide real information under certain controlled treatment conditions. Validated simulation models are useful to analyze different systems associated with the studied object (HUANG *et al.,* 2015).

Over the years, the need for more effective grain quality control has meant that various models and simulations have been created to complement the purely mechanistic approach to heat and mass balance for designing and operating aeration systems. Therefore, models describing dry matter loss (SEIB *et al*., 1980), deterioration index (TETER, 1982), insect growth (DRISCOLL *et al*., 2000), among others, were developed to obtain data that allow better management of that process. Among these models, the model to predict the growth rate of insects has gained great attention, as in addition to qualitative losses, insects are also responsible for large quantitative losses during storage. Knowing the psychrometric conditions of the intergranular air and its relationship with the growth of pest insects is essential to ensure a safe storage environment. Consequently, a projection of pest insect population dynamics provides a risk scenario of economic losses and time to formulate more efficient control strategies (ROSSINI *et al*., 2020).

Being that stated, the objective of this work was to model and simulate the growth rate of insects-plague *Rhyzopertha dominica*, *Sitophilus oryzae, Oryzaephilus surinamensis,* and *Tribolium castaneum* at the storage of corn grain, using data from digital sensors of temperature installed at Brazilian storage facilities.

MATERIAL AND METHODS

Data acquisition and system configuration

Mathematical modeling and simulation of the growth rate of the insect-plague population of *Rhyzopertha dominica*, *Sitophilus oryzae, Oryzaephilus surinamensis,* and *Tribolium castaneum* were made using digital temperature sensors installed at the silos, obtained using CERES management system (company Procer Automação e Sistemas). Data from the 1st of July to 29th September 2019, totalizing 91 days (13 weeks) were used, in which silos received corn from the first and second harvest of 2018/19. Grain temperature data from digital sensors of three Brazilian storage facilities were used. The location of these storage facilities is presented according to intermediate and immediate geographical regions (IBGE, 2017), shown in Table 1.

In each of these storage facilities, a silo equipped with digital sensors of temperature was chosen for data collection. These storage facilities were selected due to climatic variability to simulate scenarios. The CERES management system is composed of the following elements: 1) pendulums with digital temperature sensors (precision of ± 0.5 ºC); 2) stations of temperature monitoring of the grain mass, installed over the silos. Thermometry pendulums are connected to these stations, and the collected data are transmitted through wireless communication; 3) Stations that monitor the climatic conditions, as temperature, relative humidity, and precipitation events, with a precision of ± 0.5 ºC, ± 3.5% and 0.2mm, respectively; 4) actuator station that triggers the fans, installed at control board; 5) communication management station; 6) central processing, in which the management software is installed, providing visualization of the information in real-time, historical analysis and aeration configuration.

At storage facility 1, temperature data from a silo containing five pendulums, each one with 12 digital sensors, were used. The silo dimensions are, as follows: 6.43 m of diameter; 19.00 m of height (cylinder) and 3.50 m of height (cone), with a static capacity of 2,100 t, considering soybean with a bulk density of 750 kg m^{-3}. The average grain moisture content was 14.0% (w.b.). Also, the silo has a fan of 29.84 kW (40 hp). It was kept at full capacity with corn during the entire period of data collection, with the automatic rule of aeration as "cooling and corn conservation". This rule activates the fan in the case of the following conditions: zero precipitation; internal temperature equal or higher to 11ºC and external temperature added up to 5 ºC is equal or lower to the internal temperature. In addition to these conditions, if the equilibrium moisture content of corn grain is within the range of 13-16 % (w.b.), air heating will occur.

At storage facility 2, temperature data from a silo containing 9 pendulums, each one with 14 digital sensors, were used. Silo dimensions are 21.83 m of diameter; 25.68 m of height (total), being 6.30 m of cone height. Its static capacity is 6,304 t, considering soybean with a bulk density of 750 kg m^{-3}. The average moisture content of the grains was 14.0% (w.b.). The silo has two fans of 11.19 kW (15 hp) each. During the period of data collection, the amount of corn grain oscillated in its superior half part, with the automatic rule of aeration defined as "corn cooling". This rule activates the fans in the case of the following conditions: zero precipitation and external temperature added up to 4ºC is equal or lower to the internal temperature.

At storage facility 3, temperature data from a silo containing 1 pendulum with 6 digital sensors, were

Table 1. Location of storage facilities used to simulate growth rate of insect-plague

Storage facility	Location	Sea level (m)
1	Intermediate geographical region of Passo Fundo, RS, Brazil	873
2	Intermediate geographical region of Castanhal, PA, Brazil	91
3	Intermediate geographical region of Juiz de Fora, MG, Brazil	648

used. Silo dimensions are 5.48 m of diameter; 5.40 m of height (cylinder) and 1.92 m of height (cone). Its static capacity is 93 t, considering soybean with a bulk density of 750 kg m^{-3}. The average moisture content of the grains was 14.0% (w.b.). The silo has a fan of 1.12 kW (1.5 hp). During the period of data collection, the amount of corn grain oscillated in its lower half part, being completely filled in the last month of analysis. It has an automatic rule of aeration defined as "corn cooling without plenum-drastic sensor". This rule activates the fan in the case of the following conditions: zero precipitation; external temperature added up to 3ºC is equal or lower to the maximum internal temperature and external relative humidity is lower than 85%.

Modeling and simulation

The predictive microbiology assumes that the response of the population of insects-plague to the environmental conditions can be reproducible. A typical curve that describes the kinetic of the population growth process of insects-plague is composed of the latent phase (*lag*), exponential phase, and stationary phase. Few authors consider dividing the growth curve at these three phases, with the addition of the slowdown phase (DELHALLE *et al*., 2012; HALL *et al*., 2014). Delhalle *et al.* (2012) proposed to study the growth curves into five distinct phases, as shown in Figure 1.

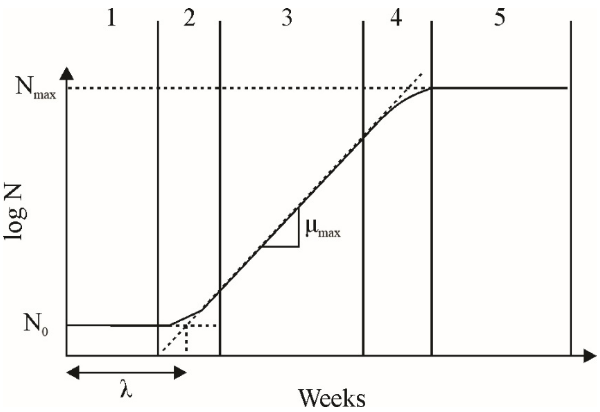


Figure 1. Insects-plague population growth curve

In which,

1 = Latent phase (*lag*): adaptation phase – the insects reproduce slowly;

2 = Acceleration phase: it points out the exit of the latent phase. In this phase, the insects begin to reproduce gradually, until attaining the maximum growth rate;

3 = Exponential phase: corresponds to the range in which the maximum growth rate is reached (μ_{max});

4 = Slowdown phase: a reduction of the growth rate occurs, preceding the stationary phase;

5 = Stationary phase: growth rate is zero and the population reaches maximum density (N_{max}). Sometimes, the subsequent phase of population reduction may occur.

In the kinetic study of the population growth is used to define: 1) duration of the latent phase (*lag*) as λ; 2) maximum growth rate as μ_{max}, which is the tangent at the inflection point; and 3) N_{max}, which is the population size limit when time tends to infinite (DELHALLE *et al*., 2012).

This study aims to analyze the prediction of population growth of insects-plague naturally infected in the storage grains mass. The average initial population was not measured. The adopted model, described by Driscoll *et al.* (2000), was employed due to its simplicity, being developed for the tropical conditions of storage, similar to Brazilian conditions, and presented good accordance with laboratory data, according to the authors. The model, after several simplifications, is shown in Equation 1.

$$r_m = f'(RH).exp(k_1.T) + ln[(k_2.(T_m - T))] \quad (1)$$

In which,

$f'(RH)$ = the function that describes the dependence of relative humidity (Equation 2).

$$f'(RH) = k_a + k_b.RH_{int} + k_c.RH_{int}^2 \quad (2)$$

In which,

r_m = population growth rate (individuals $week^{-1}$);

RH_{int} = relative humidity of the intergranular air (decimal);

k_1 and k_2 = constants of positive rate for each species (dimensionless);

T_m = mortality temperature, which limits population growth of each species (°C);

T = internal temperature of the grain mass for growth rate (°C);

k_a, k_b, and k_c = constants of the function $f'(RH)$ for each insect-plague species (dimensionless).

The values of the constants k_a, k_b, k_c, k_1, k_2, and T_m for the species described in the model are available in Table 2 (DRISCOLL *et al.,* 2000).

Modeling and simulation were conducted at Microsoft® Office Excel, using programming language, Visual *Basic for Applications*® (VBA). Throughout storage, temperature and relative humidity conditions are the critical factors. Temperatures greater than 50ºC or lower than 5ºC may exterminate or lead the insect to a hibernate state or permanent staging, and relative humidity of the intergranular air (RH) higher than 70% favors the growth of insects-plague and fungi; however, these ranges present elevated variations. The moisture content of the grain must be lower than 13% (w.b.), in order to prevent deterioration caused by water activity values (a_w) that promotes the growth of insects-plague (WERMELINGER & FERREIRA, 2013; HIMANEN *et al*., 2016; SHARMA *et al*., 2015; FERREIRA *et al.,* 2017; NEME & MOHAMMED, 2017).

Regarding aeration, two work fronts are shown: 1) control of the temperature and humidity conditions, previously reported, and 2) condition of air saturation as the gas that may be malefic to insects, such as CO_2, may cause the extermination of insects-plague within the mass grain in closed environments (RIUDAVETS *et al*., 2010; FERREIRA *et al.*, 2017).

Application of the prediction model of population growth rate

The CERES system provides historical data of thermometry of the digital sensors of all pendulums, presenting temperature readings (minimum internal, mean internal, and maximum internal) and equilibrium moisture content of the grain inferred through a hygroscopic equilibrium table, considering air heating of 2ºC when passing through the fan. In addition, the thermometry report provides external temperature and relative humidity through a monitoring station of climatic conditions. These readings are made automatically at every two hours.

According to Equations 1 and 2, to simulate scenarios, it is required data of the internal temperature of the grain mass and the intergranular relative humidity, in which these last data are unavailable at the reports of the CERES system. At Equation 1, the population growth rate presents the unity (individuals week^{-1}), thus, to apply the model, the mean weekly internal temperature was used, calculated through readings of the mean internal temperature at every 2 hours, provided by the system reports. To apply the model, the mean weekly value of equilibrium moisture content was used, at dry basis, to determine the mean weekly intergranular relative humidity, utilizing Modified Henderson Equation (THOMPSON *et al.,* 1968) (Equation 3) by isolating the term to be determined, as seen in Equation 4.

$$U_e = \left[\frac{\ln(1 - RH_{int})}{-a\,(T + b)}\right]^{\frac{1}{c}} \tag{3}$$

$$RH_{int} = 1 - \exp\{U_e{}^{c}\,[-a(T + b)]\} \tag{4}$$

In which,
RH_{int} = intergranular relative humidity (decimal);
U_e = equilibrium moisture content (%, d.b.);
T = internal temperature of the grain mass (°C);
a, b and c = model constants (dimensionless).

The values of the constants a, b, and c for corn grain are shown in Table 3.

Table 2. Constants of the models for each species of insects-plague

Specie	k_a	k_b	k_c	k_1	k_2	T_m
Rhyzopertha dominica	0.1673	0.8477	-0.6980	0.0607	0.01541	39.50
Sitophilus oryzae	-0.0399	0.2308	-0.1710	0.1430	0.05425	33.03
*Sitophilus oryzae**	0.4413	1.6090	-1.1410	0.0470	0.00753	34.55
Oryzaephilus surinamensis	0.2907	0.1273	-0.0326	0.07174	0.01625	36.13
Tribolium castaneum	0.7197	2.7010	-1.8760	0.0314	0.00242	41.29

Source: Driscoll *et al.* (2000)

* Model for RH (relative humidity) > 40%

Table 3. Model constants of equilibrium moisture content of corn grain

Product	a	b	c
Corn	8.6541 x 10^{-5}	49.810	1.8634

Source: THOMPSON *et al.* (1968)

To calculate the mean weekly temperature and the mean weekly equilibrium moisture content of the grain, the outliers were discarded, through the boxplot method, a simple way usually employed to identify discrepant values which uses statistical limits of the sample. The limit procedure uses the method based on the interquartile range (IQR), which is the difference between the third and the first quartile of the sample (Equation 5). This variability estimation is used to calculate the superior and inferior limits of the sample to identify the outliers (Equation 6). The sample data off this range are considered discrepant (SCHWERTMAN *et al.,* 2004). Identification and discard of the outliers were made using Microsoft® Office Excel.

$$IQR = Q_3 - Q_1 \quad (5)$$

In which,
IQR = interquartile range;
Q_3 = third quartile of the sample;
Q_1 = first quartile of the sample.

$$L_{sup} = \bar{X} + 1.5\ IQR$$
$$L_{inf} = \bar{X} - 1.5\ IQR \quad (6)$$

In which,
L_{sup} = superior limit;
L_{inf} = inferior limit;
$\bar{X}$ = average of the sample.

Using the population growth rates calculated using Equation 1 allowed to estimate, starting from a supposed initial sample population, the final insect population at the grain mass over time, in this case, weeks, at the exponential phase, according to Equation 7.

$$N_{insect} = N_{initial\ insect} \cdot \exp\left(N_{week} \cdot r_m\right) \quad (7)$$

In which,
N_{insect} = final insect population;
$N_{initial\ insects}$ = initial insect population;
N_{weeks} = number of weeks;
r_m = population growth rate (individuals week^{-1}).

RESULTS AND DISCUSSION

Tables 4, 5, and 6 show the values of the weekly mean temperature of the grain mass (T_{med}), the weekly mean intergranular relative humidity (RH_{med}), and population growth rate (r_m) calculated at the exponential phase for the studied insects-plague species, at storage facilities 1, 2 and 3, respectively.

Table 4. Weekly mean temperature of grain mass (T_{mean}), weekly mean intergranular relative humidity (RH_{mean}), and population growth rate (r_m) calculated at exponential phase for the studied insects-plague species at storage facility 1

Week	T_{mean} (° C)	RH_{mean} (%)	*Rhyzopertha dominica*	*Sitophilus oryzae*	*Oryzaephilus surinamensis*	*Tribolium castaneum*
			r_m (individuals week^{-1})			
1	14.6	70.1	0.057	0.107	-0.0135	-0.0656
2	10.1	53.2	-0.016	-0.127	-0.1402	-0.3528
3	9.6	68.3	-0.022	-0.090	-0.1200	-0.2850
4	10.0	65.2	-0.011	-0.078	-0.1186	-0.2747
5	10.0	68.9	-0.018	-0.076	-0.1131	-0.2679
6	10.5	60.3	-0.002	-0.075	-0.1201	-0.2786
7	10.8	61.8	0.002	-0.060	-0.1130	-0.2588
8	10.9	64.6	0.002	-0.047	-0.1055	-0.2401
9	11.3	63.4	0.008	-0.038	-0.1021	-0.2315
10	11.2	65.3	0.005	-0.038	-0.1004	-0.2284
11	11.3	60.9	0.010	-0.045	-0.1065	-0.2435
12	11.7	79.1	-0.032	-0.027	-0.0652	-0.2079
13	12.2	52.0	0.014	-0.062	-0.1093	-0.2815
Mean	11.1	64.1				

Table 5. Weekly mean temperature of the grain mass (T_{mean}), weekly mean intergranular relative humidity (HR_{mean}), and population growth rate (r_m) calculated at exponential phase for the studied insects-plague species, at storage facility 2

Week	T_{mean} (° C)	HR_{mean} (%)	*Rhyzopertha dominica*	*Sitophilus oryzae*	*Oryzaephilus surinamensis*	*Tribolium castaneum*
			r_m (individuals week^{-1})			
1	27.8	62.5	0.580	0.718	0.626	0.587
2	29.2	73.4	0.593	0.763	0.795	0.700
3	28.1	75.3	0.518	0.744	0.728	0.640
4	26.9	72.3	0.486	0.715	0.621	0.579
5	27.0	73.3	0.483	0.717	0.634	0.584
6	27.4	72.0	0.513	0.733	0.656	0.606
7	27.6	71.4	0.530	0.740	0.668	0.618
8	27.3	73.1	0.498	0.727	0.653	0.599
9	28.3	70.7	0.568	0.757	0.711	0.652
10	29.2	67.3	0.641	0.762	0.754	0.690
11	31.7	68.4	0.764	0.627	0.893	0.809
12	30.6	67.9	0.709	0.733	0.841	0.758
13	30.8	67.3	0.723	0.720	0.847	0.764
Mean	28.6	70.4				

Table 6. Weekly mean temperature of the grain mass (T_{mean}), weekly mean intergranular relative humidity (HR_{mean}), and population growth rate (r_m) calculated at exponential phase for the studied insects-plague species, at storage facility 3

Week	T_{mean} (° C)	HR_{mean} (%)	*Rhyzopertha dominica*	*Sitophilus oryzae*	*Oryzaephilus surinamensis*	*Tribolium castaneum*
			r_m (individuals week^{-1})			
1	28.9	74.5	0.564	0.758	0.777	0.680
2	17.3	73.4	0.108	0.229	0.082	0.063
3	21.4	68.0	0.266	0.443	0.251	0.273
4	24.0	73.5	0.342	0.580	0.428	0.420
5	25.2	74.0	0.392	0.639	0.511	0.486
6	20.2	72.6	0.202	0.381	0.208	0.216
7	18.5	71.0	0.154	0.292	0.124	0.125
8	20.3	76.6	0.177	0.374	0.224	0.211
9	21.1	69.0	0.252	0.429	0.241	0.261
10	21.8	71.6	0.265	0.466	0.287	0.301
11	22.6	65.0	0.325	0.501	0.307	0.327
12	24.2	64.0	0.397	0.578	0.396	0.406
13	21.9	76.8	0.231	0.459	0.313	0.298
Mean	22.1	71.5				

The majority of the population growth rates for storage facility 1 presented negative values. This represents, during the analysis period, that survival and reproduction conditions of insects-plague were less than the minimum required for its development. According to Silva *et al*. (2006), when a model does not predict populational values equal to zero, but lower or negative values, it can be concluded that this trend equals populational extermination, in a practical approach. These conditions are corroborated by the mean temperatures of grain mass, below 16ºC, and by the mean intergranular relative humidity of the air below 70 %, which delays or paralyzes the insects-plague development

(AGUIAR *et al*., 2012). Low internal temperatures are a result of the external environmental conditions; lower temperatures during the experimental period, below 15ºC, checked by the monitoring station of climatic conditions of the CERES system.

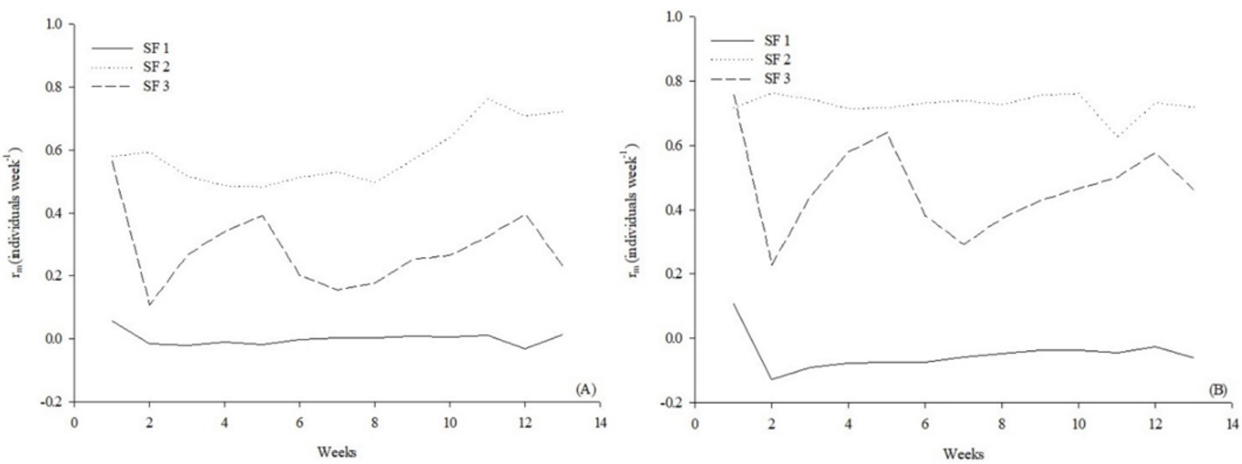
Among the assessed facilities, storage facility 2 presented the highest potential for the population growth rate of insects-plague. During the analyzed period, high temperatures at grain mass (mean of 28.6 ºC) were reported, associated with elevated values of intergranular relative humidity (mean of 70.4 %). In these conditions, the insects have propitious conditions for their fast development, becoming a high risk to the quality of the stored product (SILVA *et al*., 2006). Because of these conditions, it is recommended to adopt integrated pest management (IPM) to control these insects in grain mass.

In addition, a constant monitoring program of the ecosystem at grain mass must be employed because the weather in the region in which storage facility 2 is located is hot and moisty which favors the proliferation of insect-plague (AGUIAR *et al*., 2012).

Storage facility 3 presented intermediate values of population growth rate. Due to its lower capacity, the control of insects-plague is faster in this silo as the rotation of the product is higher showed by the product level at the silo, which oscillated over the data analysis period. Thus, the constant monitoring and control of insects-plague is required, therefore promoting, mainly, an efficient drying and cleaning procedure.

The population growth rates (ram) for the following insects-plague *Rhyzopertha Dominica*, *Sitophilus oryzae, Oryzaephilus surinamensis,* and *Tribolium castaneum* can be seen in Figure 2, at each storage facility (SF 1, SF 2 and SF 3). The highest values of population growth rate, for all species, were observed at storage facility 2, whilst the lowest values were at storage facility 1. Growth rates oscillated with close values at the three storage facilities, at a constant species. According to Sarwar (2015), among the primary insects, females of *Rhyzoperta dominica* lay up to 500 eggs spread freely between the grain, whilst adults of *Sitophilus oryzae lay*, individually, up to 450 eggs in holes in the grain. Among the secondary insects, adults of *Oryzaephilus surinamensis lay up to* 500 eggs spread in the infested grain mass, whilst females of *Tribolium castaneum lay up to* 1000 eggs. At both secondary species, the eggs cracks to produce larvae that feed on the powder and damage the grain.

It can be seen in Tables 7, 8, and 9 the population estimation for each insect-plague species studied at storage facilities 1, 2, and 3, respectively. The estimation was made considering an initial population of two adult individuals per kilogram of a representative sample of the silo at the beginning of each week. The estimations were made at the final portion of the week separately, in other words, the final estimated population by the end of 13 weeks is not cumulative.



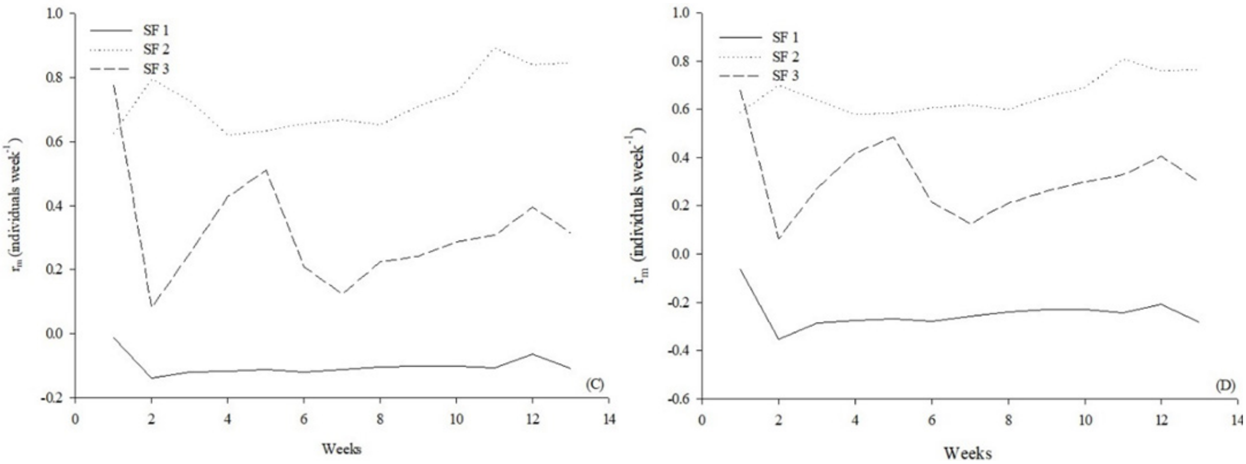


Figure 2. Populational growth rates of *Rhyzopertha dominica* (A), *Sitophilus oryzae* (B), *Oryzaephilus surinamensis* (C), and *Tribolium castaneum* (D)

Table 7. Estimation of the insects-plague population in grain mass throughout the 13 weeks at storage facility 1

Week	*Rhyzopertha dominica*	*Sitophilus oryzae*	*Oryzaephilus surinamensis*	*Tribolium castaneum*
	Population (individuals kg^{-1})			
1	2	2	2	2
2	2	2	2	1
3	2	2	1	1
4	2	1	1	1
5	2	1	1	1
6	2	1	1	0
7	2	1	1	0
8	2	1	1	0
9	2	1	1	0
10	2	1	1	0
11	2	1	1	0
12	1	1	1	0
13	2	1	0	0

Table 8. Estimation of the insect-plague population in grain mass throughout the 13 weeks at storage facility 2

Week	*Rhyzopertha dominica*	*Sitophilus oryzae*	*Oryzaephilus surinamensis*	*Tribolium castaneum*
	Population (individuals kg^{-1})			
1	4	4	4	4
2	7	9	10	8
3	9	19	18	14
4	14	35	24	20
5	22	72	48	37
6	44	162	102	76
7	82	356	215	151
8	107	670	371	241
9	333	1813	1201	705
10	1211	4083	3749	1987
11	8881	1981	36800	14637
12	9868	13250	48121	17736
13	24126	23168	121163	41348

Table 9. Estimation of the insect-plague population in grain mass throughout the 13 weeks at storage facility 3

Week	*Rhyzopertha dominica*	*Sitophilus oryzae*	*Oryzaephilus surinamensis*	*Tribolium castaneum*
	Population (individuals kg^{-1})			
1	4	4	4	4
2	2	3	2	2
3	4	8	4	5
4	8	20	11	11
5	14	49	26	23
6	7	20	7	7
7	6	15	5	5
8	8	40	12	11
9	19	95	18	21
10	28	211	35	40
11	71	495	59	73
12	234	2063	231	261
13	41	783	117	96

Storage facilities that presented the highest calculated values of population growth rates, consequently presented the highest insect-plague population over time, which is the case of storage facilities 2 and 3. At storage facility 1, due to the psychrometric conditions of the intergranular air, the insect population remained constant, with the decrease at less favorable conditions for the development of these insects.

According to Silva *et al*. (2006), the population of insects-plague at a representative sample of grain mass is limited by the amount of available food. The same authors, in analyzing the population growth of *Sitophilus zeamais* in stored wheat, reported a final population of 2430.8 insects by the end of 90 days of storage at 2 ºC, with an initial population of 1.3 adult insect per kilogram of wheat. This final population increased with the initial level of infestation, reaching 9603.4 insects per kilogram of wheat with 9.3 insects at the beginning, almost four times more than the initial population of 1.3 insects per kilogram, being the amount of food a non-limiting factor.

In the present study, under favorable growth conditions, the population became extremely large for a product considered in the sample (1 kilogram). However, such a large population is due to the exponential mathematical model to estimate the growth rate of these populations, which does not predict food availability as the limiting factor. The adopted model was validated by the authors with a satisfactory fit to the real data (DRISCOLL *et al.,* 2000). Longstaff (1981) studied the population growth of *Sitophilus oryzae* in wheat with 14% (w.b.) of moisture content, infested with 109.1 insects per kilogram. At 27ºC, the model predicted a population equivalent to 87903.8 insects per kilogram of wheat in 90 days of storage (SILVA *et al*., 2006).

For further works, we suggest the use of digital sensors of intergranular relative humidity, to generate synoptic graphics with favorable (or not) conditions for the development of insects-plague, for decision making in employing mass aeration. This work can be used as a base for further research, for instance, regarding modeling and simulation of fungi growth in stored grain, complementing the adoption of good management practice in aeration systems.

CONCLUSIONS

In this work, modeling and simulation of insect pest growth in stored corn grains were performed for different storage units located in Brazil. Based on the studies which were carried out, the following results can be highlighted:

- For all studied species of insects-plague, higher potential of populational growth rate was observed at the storage facility 2; and the lower levels for storage facility 1. Storage facility 3 presented intermediate growth rates among the other two facilities.

- Storage facilities that presented the higher potential for populational growth rates are subjected to greater risks of the elevated population of insects-plague over time.
- For the adopted conditions, the model presented in this work described perfectly the populational growth essence concerning the effect of temperature and relative humidity of the intergranular air.
- The study is indicative of the potential use of populational growth rate prediction of insects-plague aiming to adopt management practices of aeration systems.

AUTHORSHIP CONTRIBUTION STATEMENT

ZEYMER, J.S.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing; **ARAUJO, M.E.V.:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing; **SILVA, L.C.:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing; **FARIA, I.L.:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing; **OLIVEIRA, G.H.H.:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing.

DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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