Computer modelling of insect-induced hot spots in stored wheat

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¹Department of Biosystems Engineering, University of Manitoba, Winnipeg, Manitoba, Canada R3T 5V6; and ²Cereal Research Centre, Agriculture and Agri-Food Canada, Winnipeg, Manitoba, Canada R3T 2M9

Mani, S., Muir, W.E., Jayas, D.S. and White, N.D.G. 2001. Computer modelling of insect-induced hot spots in stored wheat. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada 43:4.7-4.14. A computer model of insect-induced hot spots in stored wheat was developed by combining four submodels: (1) a three-dimensional, finite element model of heat transfer, (2) a population dynamics model of the rusty grain beetle, Cryptolestes ferrugineus (Stephens), (3) a model of the heat production by C. ferrugineus, and (4) a model of the movement of C. ferrugineus. Under Winnipeg, Manitoba weather conditions, a minimum of 1300 adult C. ferrugineus introduced in the early fall at the top-centre of an unventilated 6-m diameter wheat bulk initially at 30°C caused hot spots in late winter. At an initial grain temperature of 25°C and 6000 adults introduced at the top-centre of the wheat bulk, no hot spot developed. In large diameter bins (6 to 12 m), hot spots occurred at the end of the fall and the centre temperatures reached a peak of 40°C. Due to the steep temperature gradient towards the north side of the bulk, insects initially introduced in the north side moved to the centre and caused hot spots earlier than when insects were initially introduced in the south side of the bulk.

**Keywords:** computer modelling, Cryptolestes ferrugineus, insect-induced hot spots, three-dimensional, finite element modelling.

Les auteurs ont élaboré un modèle informatisé des points chauds générés par les insectes dans le blé entreposé en combinant quatre sous-modèles : 1) un modèle tridimensionnel à éléments finis du transfert de la chaleur; 2) un modèle de la dynamique des populations du cucujide roux, le Cryptolestes ferrugineus (Stephens); 3) un modèle de la production de chaleur par le C. ferrugineus; 4) un modèle des déplacements du C. ferrugineus. Au moins 1300 cucujides roux adultes introduits au début de l’automne, en présence de températures saisonnières normales pour Winnipeg, Manitoba au centre et sur le dessus d’un lot de blé en vrac entreposé dans un silo de 6 m de diamètre ont engendré la formation de points chauds à la fin de l’hiver. Toutefois, lorsque les chercheurs ont porté, dans le cadre d’une autre expérience, la température initiale du blé à 25°C et le nombre de cucujides introduits à 6000, aucun point chaud ne s’est formé. Dans des silos plus imposants (6 à 12 m de diamètre), des points chauds sont apparus à la fin de l’automne, et les températures au centre ont atteint 40°C. En raison du fort gradient de température observé vers la face nord du silo, les insectes introduits du côté nord du silo se sont déplacés vers le centre et ont provoqué la formation de points chauds plus tôt que d’autres cucujides introduits du côté sud du silo. **Mots clés:** modélisation informatique, Cryptolestes ferrugineus, points chauds générés par des insectes, tridimensionnel, modélisation par éléments finis.

**INTRODUCTION**

Deterioration of grain due to infestations of insects, mites, and fungi is the main post-harvest factor affecting the nutritional quality and marketability of stored grain. In Canada, the total economic loss (prevention, control, and downgrading) because of stored product pests and microorganisms in grains and oilseeds is estimated to occasionally be as high as 162 million dollars per year (White 1993). In a bulk of stored grain, the heat of respiration of the insects, mites, microorganisms, and the grain itself can lead to the development of hot spots, i.e. grain pockets that are at temperatures about 35°C and warmer than the surrounding grain mass (Sinha and Wallace 1966). Two types of hot spots based on moisture content of the grain are: (1) fungi-induced hot spots in damp grain (Sinha and Wallace 1965) and (2) insect-induced hot spots in dry grain.

Knowledge of hot spot development in stored grain is essential to devise effective storage practices and pest control measures. Setting up field experiments for studying hot spots is time consuming and expensive. A more efficient method of studying hot spots is to develop computer models. Computer models can predict the effects of hot spots on the surrounding grain mass. Also, the effects on hot spot development of initial grain temperature, initial insect density, initial insect location, mechanical condition of the grain, bin size, bin wall material, date of storage, and geographical location of the bin can be simulated. Therefore a computer model was needed to simulate hot spot development in stored grain.

Several models have been developed for simulating temperature distributions in stored grain (Jayas 1995), insect population dynamics (Kawamoto et al. 1989b), and insect control (Flinn and Hagstrum 1990; Hagstrum and Flinn 1990). Most of the heat transfer models assume that the effects of internal heat generation on grain temperatures are negligible. On the other hand, population dynamics models assume that the physical environment is constant and insects do not move. Only a few attempts have been made to incorporate biological models into physical models. Flinn et al. (1992, 1997) incorporated a population dynamics model of Cryptolestes ferrugineus (Stephens) into a heat transfer model (Muir et al. 1980), but there was no feedback from the population dynamics model to the heat transfer model. Heat production and movement of the insects were not included in the model. No computer model has been developed for simulating hot spots in stored grain, a phenomenon that involves heat transfer, population dynamics, heat production, and insect movement.

The objectives of this research were: (1) to develop a computer model for predicting hot spots induced by C. ferrugineus in stored wheat; (2) to predict the effects on hot
spot development of the initial insect population, initial grain
temperature, bin size, and location of the initial infestation; (3)
to predict the locations most vulnerable to the development of
hot spots in a grain bulk; and (4) to predict the temperature
variations in hot spots with respect to the insect population.

**SUBMODELS OF A HOT SPOT MODEL**

Temperature is the most important abiotic variable affecting the
multiplication, rate of heat production, and distribution of
insects in stored grain (Kawamoto et al. 1989a; Oxley 1948).
Temperatures in stored grain bulks vary in all three directions.
Therefore, a three-dimensional model of heat transfer was used
for studying grain temperatures in the hot spot model. The three-
dimensional, finite element model of heat transfer developed by
Alagusundaram et al. (1990) was used in the hot spot model to
predict grain temperatures.

The population dynamics of *C. ferrugineus* was simulated in the
hot spot model because *C. ferrugineus* is the predominant
insect pest of stored cereals under Canadian storage conditions
and the dominant insect pest in developing hot spots (Sinha and
Wallace 1966). The population dynamics model of *C. ferrugineus*
developed by Kawamoto et al. (1989b) was chosen because this model was developed based on the results
of experiments that were done under Canadian storage
conditions. Heat production rates of *C. ferrugineus* were
calculated using the equations developed by Cofie-Agblor et al.
experiments to study the movement of *C. ferrugineus* in response to temperature gradients in stored wheat. Results of
their experiments were used in the hot spot model for simulating
the insect movement.

**MOVEMENT OF RUSTY GRAIN BEETLES**

*Cryptolestes ferrugineus* move from cooler to warmer grain
even at temperature gradients as low as 3.7°C/m (Flinn and
Hagstrum 1998). Therefore, 1°C was considered as the
minimum temperature difference between adjacent elements to
cause *C. ferrugineus* to move to the warmer element. Insect
movement from an element was simulated when any of the
following conditions existed: (1) the temperature of the element
was 1°C less than the temperature of any adjacent element, (2)
the total adult population of the element was equal to or greater
than 1000 adults/kg of wheat, or (3) the temperature of the
element was more than 35°C.

**HOT SPOTS**

A hot spot was assumed to have developed in a spatial element
when: (1) its average temperature was greater than 35°C and (2)
its adult population was at least 100 adults/kg of wheat. It was
assumed that grain in a hot spot was completely spoiled and
further reproduction of insects was not feasible in a hot spot.
Insects would emigrate from hot spots but no insects would
immigrate to one.

**ASSUMPTIONS MADE FOR THE HOT SPOT MODEL**

The following assumptions were made to develop the hot spot model:

1. The physical properties of wheat throughout the bulk and
throughout the simulation period were assumed constant,
however, variable properties could be handled by modifying
the model slightly.
2. The effects of moisture content and gas concentration were
assumed negligible.
3. A minimum of two adults were needed for insect
multiplication in a grain pocket and the sex ratio
(females/(males+females)) was 0.57 (Kawamoto et al.
1989b) i.e. for an initial infestation of 600 adults there were
340 adult females and 260 adult males.
4. The contribution by other insect species, mites, and fungi to
internal heat generation in the stored grain was negligible.
5. The effects of physiological age of the insects on heat
production and movement of adult *C. ferrugineus* were
negligible.
6. The heat production rate of 4 week old adults at a density of
2500 insects/200 g of wheat (Cofie-Agblor et al. 1996b) was
the heat production rate of adults in a population of varying
physiological ages and densities.
7. The emigration of insects from a hot spot to the surrounding
grain bulk was not affected by the decreasing temperature
gradient. Similarly, when the movement was caused by high
densities of insects, then the movement was not determined
by a temperature difference but rather by the insects
migrating in search of food.

**SIMULATION PROCEDURE**

The simulated bin was filled with wheat to a depth of 6 m and
was cylindrical in shape. The top grain surface was levelled and
the bottom surface was a concrete floor. The simulated grain bin
was discretized into five layers containing 440 three-
dimensional, linear, hexahedron elements [88 elements in each
layer] (Mani 1999; Mani et al. 1999). Thickness of each layer
was 1.2 m. The temperature of each element was calculated as
the average of its eight nodal temperatures. The average of the
temperatures of the four centre elements in the middle layer was
calculated and defined as the average centre temperature. A grid
generation program was written to generate three-dimensional
grid nodes from two-dimensional grid nodes. Hourly ambient
temperatures, wind velocities, and solar radiation on a
horizontal surface for Winnipeg, Manitoba (01 September 1986
to 31 August 1987) were used in the hot spot model. The mean
temperature of the simulation period was 2.3°C higher than the
normal temperature of 2.4°C for the standard normal period of
1951 to 1980 (Environment Canada 1986). The hot spot model
would handle 1, 2, or, 3 Gauss quadrature in each plane. Thermal
and physical properties of wheat were: specific heat, 1700 J kg⁻¹ K⁻¹;
thermal conductivity, 0.12 W m⁻¹ K⁻¹; and bulk
density, 772 kg/m³ (ASAE 1997). The longwave and shortwave
emissivities, 0.28 and 0.89, respectively, for galvanized iron
were used (Alagusundaram et al. 1990).

**RESULTS AND DISCUSSION**

**Effects of initial insect densities**

The simulated centre temperature of a 6-m diameter bin level-
filled on 1 September with 14.5% moisture content wheat at
Fig. 1. Predicted average centre-temperatures for five initial densities of *C. ferrugineus* (IID – initial insect density of adults) introduced on 01 September 1986 in a 350-kg grain pocket at the top-centre of the grain bulk in a 6-m diameter bin filled with wheat to a depth of 6 m at Winnipeg, Manitoba.

During summer, the centre temperature of the bulk in which 31 000 adults were introduced was lower than the centre temperature of the bulk in which 6000 adults were introduced. This was because with 31 000 adults the hot spot occurred earlier and then the insects migrated out of the centre elements. In summary, under Winnipeg weather conditions when a minimum of 1300 adults are introduced at the top-centre of a 6-m diameter bulk a hot spot at the centre of the bulk may develop in the late winter.

**Effects of initial grain temperatures**

Simulations to predict the effects on hot spot development of initial grain temperatures and initial insect locations were all done for an initial insect infestation of 6000 adults. At an initial grain temperature of 25°C, no hot spot was simulated and the centre temperature decreased to a minimum temperature of 0°C in the following summer (Fig. 1). Introducing 600 adults (1 newly emerged, mated female/kg of wheat) in a 350-kg grain pocket at the top-centre of the bulk caused the centre temperature to rise a maximum of 1°C above the temperatures in an uninfested bin (Fig. 1). Due to heat loss from the top surface, temperatures at the top-centre decreased causing the adults to move from the top-centre to the warmer centre of the bulk. By the end of summer 1 year later, the centre temperature in the bin infested with 600 adults decreased to the temperature in the bin with no insects. The heat produced by this low initial infestation, 600 adults in the bin, was not sufficient to increase the grain temperatures to the level favourable for insect multiplication.

When the grain was infested with 1300 adults (2 newly emerged females/kg of wheat) at the top-centre of the bulk, a hot spot developed and a maximum temperature of 39°C was predicted at the centre by early winter (Fig. 1). No increase in centre temperature was predicted for the first 2 months of simulation because of the time needed for insects to move from the top-centre to the centre of the grain bulk and to multiply at the centre of the grain bulk. Because the thermal diffusivity of wheat is low and hot spots developed in the spatial elements surrounding the centre of the bulk, the centre temperature remained warm for 8 weeks after reaching the peak temperature. The average centre temperature of the bulk then decreased as heat was transferred out through the wall and top surface and no additional heat was generated in the centre elements by the insects because they had moved out from the centre of the bulk.

For an initial insect density of 31 000 adults (50 newly emerged females/kg of wheat) at the top-centre of the bulk, a hot spot developed at the centre of the bulk at the end of the fall.

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**Effects of initial grain temperatures**

Simulations to predict the effects on hot spot development of initial grain temperatures and initial insect locations were all done for an initial insect infestation of 6000 adults. At an initial grain temperature of 25°C, no hot spot was simulated and the centre temperature decreased to a minimum temperature of 0°C in the following summer (Fig. 2). *Cryptolestes ferrugineus* are not able to develop and multiply but they are able to survive at temperatures below 17°C (Fields and White 1997) and their heat production is also low at low grain temperatures (Cofie-Agblor et al. 1996b). Adults can tolerate >15°C for 2 wk or >10°C for 6 wk (Mills 1990). Although the insects migrated to the centre of the bulk they had little effect on the centre temperature. Hence, the centre temperature of the grain bulk with the initial temperature of 25°C did not increase. This lack of hot spot development is similar to an initial grain temperature of 30°C and an addition of 600 adults. Even though no hot spot developed, the grain is infested and under the Canadian grading system the grain would be rejected (Anonymous 1989).

At an initial grain temperature of 30°C, insects introduced at the top-centre migrated to and multiplied at the centre of the bulk and developed a hot spot in December. The peak temperature of 39°C was reached in January. A grain temperature of 30°C is the optimal temperature for *C. ferrugineus* to multiply (Kawamoto et al. 1989a). At an initial
Fig. 3. Predicted average centre-temperatures for bins filled with wheat to a depth of 6 m at Winnipeg, Manitoba when 9 newly-emerged *C. ferrugineus* females/kg of wheat were introduced at the top-centre of the grain bulk on 01 September 1986. (Total initial-infestations per bin were: 4 m diameter – 1350; 6 m – 3150; 8.5 m – 6030; and 12 m – 12 600).

Effects of bin diameter

The possibility and duration of a hot spot increased as bin diameter increased (Fig. 3). The larger the bin diameter, the earlier the hot spot occurred. In 6.0, 8.5, and 12.0-m diameter bins, hot spots developed when 9 newly emerged females/kg of wheat were initially introduced into a grain pocket at the top-centre of a 6-m tall wheat bulk. (Total initial infestations per bin varied as follows: 4 m diameter – 1350; 6 m – 3150; 8.5 m – 6030; and 12 m – 12 600.) In a 4-m diameter bin, no hot spot was simulated (Fig. 3). When the total initial infestation was held constant at 6000 adults (i.e. initial insect densities of newly emerged females/kg of wheat varied as follows: 4-m diameter – 23; 6-m – 9; 8.5-m – 5; and 12-m – 2.6) the temperature trends were the same as that with the initial density of 9 females/kg of wheat except that in the 12-m diameter bin the centre temperatures were about 2°C cooler in the following summer (data not shown).

Effects of initial insect locations

When 6000 insects were introduced at the top-centre of a 6-m diameter wheat bulk (0.6 m depth), they migrated to and multiplied at the centre of the bulk and developed a hot spot (Fig. 4). Insects introduced at the centre of the bulk (3.0 m depth) developed hot spots 1 month later. In both cases, insects spread throughout the wheat bulk and developed hot spots extensively. During the late fall, the average centre temperature when insects were introduced at the top-centre was higher than the average centre temperature when insects were introduced at the centre of the wheat bulk. When insects were introduced at the centre of the bulk, the initially high insect density caused a decrease in oviposition rate (the number of eggs produced per female per unit time) and an increase in mortality rate. When insects were introduced at the top-centre, the number of insects that moved to the centre was determined by the temperature gradients in the grain bulk and hence the insect population at the centre was not high enough to cause a reduction in oviposition rates and an increase in mortality rates. During summer, the centre temperature of the bulk in which insects were initially introduced at the centre was higher than the centre temperature of the bulk in which insects were initially introduced at the top-centre. This was because of migration of more insects to the surrounding bulk from the centre of the bulk in which insects were initially introduced at the centre (Fig. 4). When the insects were introduced at the bottom-centre of the bulk (5.4 m depth), fewer insects moved to the centre of the bulk due to the prevailing lower temperature gradient between the bottom-centre and the centre. The centre temperature reached the peak of 35°C in the early winter (Fig. 4) and developed a hot spot at the centre of the bulk. Insects did not spread throughout the wheat bulk and develop hot spots extensively. No hot spot was predicted at the bottom-centre of the bulk because of the unfavourable temperatures for insect multiplication at the bottom-centre.

Simulated results were compared for the introduction of 6000 adult *C. ferrugineus* on the top-surface of the bulk at three locations: (1) centre-axis of the bulk, (2) south-east quarter at 2.2 m radius, and (3) north-east quarter at 2.2 m radius (Fig. 5). The temperature gradient between the north side of the bulk and the centre of the grain bulk was higher than the temperature gradient between the south side of the bulk and the centre of the bulk. Hence, insects introduced near the north side of the grain bulk temperature of 35°C, insects induced a hot spot at the centre of the grain bulk within 3 months in November. The centre temperature remained warm for 8 weeks and then decreased as the rate of heat loss from the centre increased. In summary, at low initial grain temperatures (<25°C), there is little possibility for hot spot development in stored grain in Western Canada.
bulk moved to the centre of the bulk earlier than when they were introduced near the south side. When the insects were introduced on the north side more insects moved to the centre and then to the wheat bulk surrounding the centre element than when they were introduced on the south side. Hence the average centre temperatures in the spring and the summer when insects were introduced on the north were higher than when they were introduced on the south.

Predicted temperatures and insect densities in a hot spot

During the first 4 weeks of storage, adults moved from the top-centre introduction point to a 350-kg grain pocket at the centre of the bulk (Fig. 6). Temperatures and adult and immature populations (sum of the populations of 1\textsuperscript{st}, 2\textsuperscript{nd}, 3\textsuperscript{rd}, and 4\textsuperscript{th} instar larvae) at the centre then increased. The lag between the rise in adult and immature populations was because of the developmental time of eggs into 1\textsuperscript{st} instar larvae. The increase in the adult population was due to the development of immatures and the migration of adults from the surrounding grain bulk. By 8 weeks (23 October), the 350-kg grain pocket developed into a hot spot having populations of 550 adults/kg and 10 200 immatures/kg (Fig. 6). Hot spot temperature spiked to 35.6°C.

When the hot spot reached 35°C, the adults were assumed to migrate from the hot spot to the surrounding grain. Most of the immatures were assumed to die because of the high temperature and high insect population in the hot spot. The temperatures at the centre of the bulk were greater than 33°C (Fig. 7). Because the hot spot spread around the centre of the bulk, temperatures at the centre increased and reached 38°C or higher on 01 December. On 01 January most of the central bulk was at 38°C or higher. Temperatures on the south side were higher than the temperatures on the north side (Fig. 7). Due to the migration of insects and heat losses through the wall, temperatures at the centre of the bulk decreased after January 1987.

In Fig. 8 the densely shaded areas are hot spots, the lightly shaded areas represent lightly infested wheat, and unshaded areas represent wheat without insects. After the hot spot developed, the adult population in hot spots can be zero because the adults were assumed to migrate from the hot spots. The first occurrence of a hot spot was detected at the centre of the bulk (3 m depth). Because the insects were initially introduced at the top-centre of the bulk, the insects moved downward and laterally to the warmest region. The mass of wheat infested by insects increased because of the movement of the adults. The predicted locations of hot spots tended towards the south side of the bulk because of the higher temperatures in the south side.
Fig. 7. Predicted isotherms (°C) at the 3-m depth in a 6-m diameter bin filled with wheat to a depth of 6 m at Winnipeg, Manitoba when 6000 adult *C. ferrugineus* were introduced at the top-centre of the grain bulk on 01 September 1986 with an initial grain temperature of 30°C.

**CONCLUSIONS**

Hot spots induced by *C. ferrugineus* in grain storage bins that are located at Winnipeg, Manitoba were simulated by using the hot spot model. Starting date of the simulations was 01 Sep 1986 and the temperatures and insect population were simulated for a one year period with 1986-87 weather data. The following conclusions were drawn from this research:

1. A *C. ferrugineus*-induced hot spot model was developed by combining the following submodels: a three-dimensional, finite element model of heat transfer, a population dynamics model of *C. ferrugineus*, a model of heat production of *C. ferrugineus*, and a model of the movement of adult *C. ferrugineus*.

2. In a 6-m diameter bin filled with wheat at 30°C to a depth of 6 m, 600 adults (1 newly emerged, mated female/kg of wheat in the element) initially introduced at the top-centre of the bulk did not develop hot spots but an initial insect density of 1300 adults (2 newly emerged females/kg of wheat) developed hot spots at the centre of the grain bulk. In grain bulks with an initial grain temperature of 25°C and 6000 adults initially introduced at the top-centre of the bulk, no hot spot was predicted. In grain bulks with initial grain temperatures of 30°C and 35°C, hot spots were predicted at the centre of the grain bulk. In larger diameter bins infested with either 9 newly emerged females/kg of wheat or a total of 6000 adults at the top-centre of the bulk hot spots developed earlier and centre temperatures remained warmer than in smaller diameter bins. Insects introduced along the north side of the grain bulk migrated to the centre of the bulk earlier than when they were introduced along the south side.

3. The centre of the bulk was the most favorable location for insect multiplication and hence most vulnerable to hot spot development.

4. A peak average centre temperature of 39°C was predicted in a grain bulk that was affected by hot spots. A peak adult population of 550 adults/kg of wheat was reached in a 350–kg hot spot developed at the centre of the bulk.

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**REFERENCES**


Fig. 8. Predicted distribution of adult *C. ferrugineus* in a 6-m diameter bin filled with wheat to a depth of 6 m at Winnipeg, Manitoba when 6000 adults were introduced at the top-centre of the grain bulk on 01 September 1986 with an initial grain temperature of 30°C.


