COMPUTER MODELLING OF INSECT-INDUCED HOT SPOTS IN STORED GRAIN

BY

SESHADRI MANI

A Thesis

Submitted to the Faculty of Graduate Studies

in Partial Fulfillment of the Requirements

for the Degree of

MASTER OF SCIENCE

Department of Biosystems Engineering

University of Manitoba

Winnipeg, Manitoba

0-612-41743-3

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

*****

COPYRIGHT PERMISSION PAGE

COMPUTER MODELLING OF INSECT-INDUCED HOT SPOTS IN STORED GRAIN

BY

SESHADRI MANI

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University

of Manitoba in partial fulfillment of the requirements of the degree

of

MASTER OF SCIENCE

ABSTRACT

A computer model of the development of insect-induced hot spots in stored grain 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 heat production of *C. ferrugineus*, and (4) a model of movement of *C. ferrugineus*. The higher the initial insect density and the initial grain temperature, the higher and the earlier was the possibility for hot spot occurrences. In large diameter bins, hot spots occurred at the end of fall and the centre temperatures reached a peak of 40°C. Due to the steep temperature gradient prevailing along the north side of the bulk, insects initially introduced in the north side moved to the centre and caused hot spots earlier than when the insects were initially introduced in the south side of the bulk. In a validation experiment, no hot spot was developed in two bins of 1-m diameter filled with wheat of an initial grain temperature of 28°C and an initial moisture content of 13.2% to a depth of 1-m and located in a laboratory; 10,000 adults were initially introduced at the centre of the grain bulk. For the experimental conditions, the hot spot model predicted no possibility for hot spot development. The hot spot model includes the feedback from the insect model to the temperature model whereas a published spatial model does not include that feedback. The hot spot model predicted a maximum insect population of 120 adults/kg and temperature of 39°C in a hot spot developed at the centre of a 8.5-m diameter wheat bulk with an initial grain temperature of 30°C and 10,000 adults introduced at the centre of the bulk. For the same simulation conditions, the spatial model predicted a maximum of 500 adults/kg and predicted no increase in the temperatures.

ACKNOWLEDGMENTS

I sincerely thank Dr. W. E. Muir for his invaluable guidance and constant encouragement during my project work. Thanks for his willingness to share his knowledge, whenever I had problems during the course of this study.

I also express my thanks to my committee members Dr. D. S. Jayas, Dr. N. D. G. White, and Dr. P. G. Fields, for their continuous support. I wish to acknowledge the Natural Sciences and Engineering Research Council of Canada for providing financial assistance.

I thank Dr. Paul Flinn, Dr. S. M. Woods, and Dr. Cofie-Agblor for their support on computer programs. I thank Matt McDonald, Jack Putnam, and Dale Bourns for their help. Special thanks to Leslie Toews for her help in setting up the experiment. Special thanks to my colleagues Balaji, Jeyam, Chithra, Leanne, and other friends for their encouragement.

Finally I would like to thank my parents, brothers, and sisters for their moral support.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS *

a_0, a_n	Fourier coefficient (°C),
A	physiological age of adult insects (degree days),
b_0 , b_n	Fourier coefficient (°C),
B	scaling parameter for oviposition rate calculation (981 ± 35),
[B]	matrix for shape function calculation
c_p	specific heat of grain ($J{\bullet}kg^{-1}{\bullet}K^{-1}$),
[C]	global capacitance matrix,
C	shape parameter for oviposition rate calculation (1.26 ± 0.03),
d	diameter of the grain bin (m),
dV	derivative of volume integration,
dS_2 , dS_3	derivative on surfaces S_2 and S_3,
D	day of the year starting on Jan 1 (d),
[D]	matrix for grain properties,
E_{GG}	maximum total number of eggs produced by a female during her life time under the optimal condition (687 ± 159 eggs per female),
f_a (T'), f_L (T'), f_H (T')	coefficients of immature development rate,
{F}	global force vector,
F_{be}	radiation shape factor from bin to earth (0.5),
F_{bs}	radiation shape factor from bin to sky (0.5),
G	number of eggs produced by a female insect while its physiological age increases from A_i to A_j,
h_c	convective heat transfer coefficient ($W{\bullet}m^{-2}{\bullet}K^{-1}$),

* All symbols related to biological aspects represent rusty grain beetles

h_{l2} heat production rate of second instar larvae (μW/larva),

h_{l3} heat production rate of third instar larvae (μW/larva),

h_{l4} heat production rate of fourth instar larvae (μW/larva),

h_p heat production rate of adults (μW/insect),

H measured radiation on a horizontal surface ($W\bullet m^{-2}$),

H_a, H_L, H_H parameters expressing the magnitude of the effects of temperature on developmental rate of immature, $H_a = (1.26 \pm 5.23) \times 10^4$, $H_L = (-2.38 \pm 5.45) \times 10^4$, $H_H = (1.76 \pm 3.57) \times 10^4$,

H_b beam radiation on a horizontal surface ($W\bullet m^{-2}$),

H_d diffuse radiation on a horizontal surface ($W\bullet m^{-2}$),

H_v radiation on a vertical surface ($W\bullet m^{-2}$),

H_0 extraterrestrial radiation on a horizontal surface ($W\bullet m^{-2}$),

I_{sc} solar constant (1353 $W\bullet m^{-2}$),

k thermal conductivity of the grain ($W\bullet m^{-1}\bullet K^{-1}$),

$[K]$ global conductance matrix,

k_x, k_y, k_z thermal conductivity of the grain in x, y, and z coordinates respectively ($W\bullet m^{-1}\bullet K^{-1}$),

K_p ratio of diffuse radiation (H_d) to measured radiation on a horizontal surface (H),

K_T ratio of measured radiation on a horizontal surface (H) to the extra terrestrial radiation (H_0),

l_x, l_y, l_z direction cosines at x, y, and z directions,

M modification factor due to low or high temperature (M_{LH}), low relative humidity (M_{DRY}), and high density (M_{DEN}),

M_c moisture content of grain (%, wet mass basis),

M_t measured temperatures (°C)

n	number of observations
n_s	incremental term for soil temperature calculation (1 to 6),
N	change in insect density (number of insects/kg of wheat),
$[N]$	matrix of interpolation functions,
$[N]^T$	transpose of matrix of interpolation function,
N_{ad}	number of females/g of wheat,
N_{IMM}	number of immature insects/g of wheat,
N_u	Nusselt number,
P_r	Prandl number,
P_{DE}	egg developmental rate coefficient ($1.69 \pm 0.03\ d^{-1} \bullet °C^{-1}$),
P_{MH}	coefficient for high temperature inhibition factor ($0.286 \pm 0.074\ °C^{-1}$),
P_{ML}	coefficient for low temperature inhibition factor ($0.229 \pm 0.041\ °C^{-1}$),
P_{MDEN}	coefficient for adult density inhibition factor (0.520 ± 0.060),
P_{MDRY}	coefficient for low relative humidity inhibition factor ($(1.82 \pm 0.77) \times 10^{-3}$ $°C^{-1} \bullet \%RH^{-1}$),
P_{SHA}	parameter for thermal stress on adults at high temperatures (101.3 ± 2.0),
P_{SHB}	parameter for thermal stress on adults at high temperatures ($(-3.29 \pm 0.06) \times 10^4$),
P_{SLA}	parameter for thermal stress on adults at low temperatures (-36.1 ± 1.5),
P_{SLB}	parameter for thermal stress on adults at low temperatures ($(8.58 \pm 0.42) \times 10^3$),
P_{UEH}	coefficient for high temperature egg mortality factor ($(3.44 \pm 1.90) \times 10^{-2}\ d^{-1} \bullet °C^{-1}$),
P_{UIH}	coefficient for high temperature immature mortality factor ($(1.92 \pm 0.44) \times 10^{-2}$ $d^{-1} \bullet °C^{-1}$),
P_{UEDR}	coefficient for low humidity egg mortality factor ($1.74 \times 10^{-2}\ d^{-1} \bullet \%RH^{-1}$),
P_{UIDEN}	coefficient for density immature mortality factor ($(8.74 \pm 2.64) \times 10^{-3}$ density of immatures$^{-1} \bullet d^{-1}$),

P_{UIDR}	coefficient for low humidity immature mortality factor (1.76×10^{-2} d^{-1}•%RH^{-1}),
P_t	predicted temperatures (°C)
q_r	net solar radiation (W•m^{-2}),
q_d	direct solar radiation (W•m^{-2}),
q_e	earth to bin radiation (W•m^{-2}),
q_f	diffuse solar radiation (W•m^{-2}),
q_o	bin to surrounding radiation (W•m^{-2}),
q_s	sky to bin radiation (W•m^{-2}),
$\dot{q}$	internal heat generation in an element (W•m^{-3}),
R_b	ratio of cosine of angle of incidence to cosine of zenith angle,
R_e	Reynolds number,
R_{egg}	developmental rate of eggs (d^{-1}),
R_{imm}	developmental rate of immature stage (d^{-1}),
R_{25}	standard developmental rate of immature at 298.2 K, ($(4.13 \pm 5.79) \times 10^{-2}$ d^{-1}),
s_h	angle the plane makes with the horizontal (rad),
S	cumulative thermal stress on adults (used for calculating the adult mortality rate, K),
S_1	surface on which temperature is prescribed,
S_2	surface on radiation boundary,
S_3	surface on convection boundary,
t	time domain (s),
T	nodal temperatures (K),
{T}	nodal temperature vector,
T_0	prescribed temperature on surface S1 (K),
T_a	ambient temperature (K),
T_i	initial grain temperature (K),

T_s	average sky temperature (210 K),
T_s^e	average surface temperature of the element on the radiation surface boundary (K),
T_{ave}	average temperature of the element (°C),
T_{ave}'	absolute average temperature of the element (K),
T'_H	temperature at which the basic developmental rate is reduced by about one-half by the inhibitive effect of high temperature (303.7 ± 26.8 K),
T'_L	temperature at which the basic developmental rate is reduced by about one-half by the inhibitive effect of low temperature (293.0 ± 32.3 K),
T_{AG}	threshold temperature for physiological age calculation (16.6 ± 0.4°C),
T_{DE}	base temperature for egg developmental rate calculation (15.3 ± 0.3°C),
T_{MH}	threshold temperature for high temperature inhibition factor (35.0°C),
T_{ML}	threshold temperature for low temperature inhibition factor (29.4°C),
T_{MDRY}	threshold temperature for low relative humidity inhibition factor (22.5°C),
T_{UEH}	threshold temperature for high-temperature egg mortality factor (35.0 ± 1.8°C),
T_{UIH}	threshold temperature for high-temperature immature mortality factor (37.3 ± 0.8°C),
U	instantaneous mortality rate of insects (d^{-1}),
U_B	basic mortality rate at optimal conditions, $U_{EGG,B}$ for egg stage and $U_{IMM,B}$ for immature stage (d^{-1}),
U_{DEN}	mortality rate due to high density, $U_{IMM,DEN}$ for immature stage (d^{-1}),
U_{DRY}	mortality rate due to low relative humidity, $U_{EGG,DRY}$ for egg stage and $U_{IMM,DRY}$ for immature stage (d^{-1}),
U_H	mortality rate due to high temperature, $U_{EGG,H}$ for egg stage and $U_{IMM,H}$ for immature stage (d^{-1}),

U_L	mortality rate due to low temperature (d^{-1}),
v	wind velocity ($m \bullet s^{-1}$),
V	numerical integration over volume,
W	relative humidity (%),
W_t	threshold relative humidity for immature developmental rate calculation (75%),
x, y, z	coordinates of a nodal point,
z	distance of the corresponding node from the circumference of the bin (m),
ρ	density of grain ($kg \bullet m^{-3}$),
θ	time domain approximation factor,
ψ_T	angle of incidence of beam radiation (rad),
ψ_Z	zenith angle (rad),
μ	viscosity of air ($N \bullet s \bullet m^{-2}$),
σ	Stefen Boltzman constant (5.67×10^{-8}, $W \bullet m^{-2} \bullet K^{-4}$),
α	longwave absorptivity of the bin wall material (0.28),
α_s	thermal diffusivity of soil beneath the bottom layer of the bin ($m^2 \bullet s^{-1}$),
ε	emissivity of the bin wall material (0.28),
γ	shortwave absorptivity (0.89),
ν	ground reflectance,
ϕ	latitude (rad),
δ	declination (rad),
γ	surface azimuth angle (rad),
ω	hour angle (rad),
ω_s	sunrise hour angle (rad),
Δt	time step (s).

1. INTRODUCTION

Canada produces about 40 Mt of cereal grains per year and stands sixth in international production and second in exports (CGC 1996). Grain storage capacity of Western Canada is 82 Mt (Muir 1997), almost double its annual production. Of which, 80% is on-farm storage (Muir 1997). Most farms in Canada have on-farm storage capacity of 1.5 to 2.0 times their average annual production to be able to safely store large carryovers and large harvests, and these systems must maintain grain quality for 2 years or more (Muir 1980). Both quality and quantity losses occur during storage. Deterioration of grain due to infestations of insects, mites, and fungi is the main factor affecting the nutritional quality and marketability of the 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 be up to 162 M$/yr (White 1993).

Over 100 species of pest insects and over 355 species of mites have been recorded in stored products throughout the world (White 1995). 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 higher temperatures 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. Hot spots lead to rapid deterioration of the stored grain. Heavy losses due to hot spots occur especially during winter because of the cold ambient temperatures and warm centre temperatures of grain bulks (Sinha and Wallace 1966).

Knowledge of hot spot development in stored grain is an essential factor for devising effective storage practices and 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 needs to be developed for simulating hot spot development in stored grain. Computer models have been used to simulate variables such as temperature, moisture content, CO_2 concentration, insect population, and strategies for insect control that define stored-grain ecosystems (Alagusundaram et al. 1990a; Smith and Sokhansanj 1990; Jayas et al. 1988; Kawamoto et al. 1989a, 1990, and 1992; Hagstrum and Flinn 1990).

Many models have been developed for simulating temperature distributions in stored grain (Alagusundaram et al. 1990a, 1990b; Bala et al. 1989, Converse et al. 1969, Jayas et al. 1994, Metzger and Muir 1983, Muir 1970, Muir et al. 1980, O'Dowd et al. 1988, Sarker and Otto 1991), insect population dynamics (Kawamoto et al. 1989a), and insect control (Flinn and Hagstrum 1990, Hagstrum and Flinn 1990, Hagstrum and Milliken 1988). 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. These computer models simulated specific processes of stored-grain ecosystems such as heat transfer and population dynamics.

Only a few attempts have been made to incorporate biological models into physical models. Flinn et al. (1992 and 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. A hot spot model could be used to predict the possible occurrence and location of insect-induced hot spots as a function of several variables such as grain bin size, initial grain temperature, initial insect density, and initial insect location in the bin.

To study the stored-grain ecosystems completely a comprehensive model; which simulates all abiotic variables, insect population growth, and interactions among individuals; will have to be developed. The hot spot model developed in this research project can be made more comprehensive in the future by adding submodels of moisture content, CO_2 concentration, population dynamics, heat production of other insect species, and fungal infection. The objectives of this research are:

(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 development of hot spots in the grain bulk;

(4) to predict the temperature variations in hot spots with respect to the insect population;

(5) to compare predicted temperatures and insect population with those observed in an experimental setup; and

(6) to compare temperatures and insect population predicted by my model with those predicted by the spatial model developed by Flinn et al. (1992).

2. REVIEW OF LITERATURE

2. 1 Hot spot development in stored grain

2. 1. 1 Hot spots The spoilage of stored grain usually begins in localized pockets, which are called hot spots, where grain temperatures and moisture contents are conducive to the growth of stored product insects, fungi, and mites (Muir 1970; Sinha 1961, 1970, and 1974). Sinha (1967) defined two types of hot spots: (1) fungi-induced hot spots in damp grain (moisture contents usually greater than 17% wet mass basis), and (2) insect-induced hot spots in dry grain (moisture contents usually less than 14.5% wet mass basis). Throughout this thesis moisture contents (m. c.) are given in wet mass basis unless otherwise specified.

2. 1. 2 Fungi-induced hot spots One or more small pockets in a large bulk of relatively dry grain may spoil when a load of damp grain is placed in a bin of dry grain or where rain or snow enters through the bin structure (Muir et al. 1987). Enzymatic action and growth of molds in damp grain are associated with increasing grain temperatures and developing hot spots when no insects are present (Back and Cotton 1924; Wallace and Sinha 1962).

Sinha and Wallace (1965) studied the ecology of a fungi-induced hot spot. A hot spot was artificially induced by introducing wheat at 23% moisture content in a wheat bulk at 14.5% moisture content. Because many species of *Penicillium* grow well at 23% moisture content, the percentage of seeds infected by *Penicillium* increased in the hot spot. Germinability of the wheat in the hot spot decreased. The maximum grain temperature reached was 64°C. Since fungi could not grow beyond 55°C, they concluded that heating from 55 to 64°C is caused by the activities of bacteria. The heated area extended at least

0.5-m from the center of the hot spot. The hot spot cooled to the temperature of the surrounding grain 3 wk after it reached the maximum of 64°C because fungi can not withstand temperatures beyond 55°C.

2. 1. 3 Insect-induced hot spots Oxley (1948) studied many cases of heating in dry grain and concluded that in every case the cause was an insect infestation. In such cases grain temperature did not rise above 40°C. Oxley (1948) observed that with grain moisture content below 14.5% (i.e., dry grain) the heat produced by respiration of the grain and microorganisms was negligible.

Hot spots are affected mainly by grain temperature, moisture content, insect development rate, and insect population density (Howe 1962). Insect-induced hot spots in Canada are often associated with infestations by *Cryptolestes ferrugineus* (Coleoptera Cucujidae) (Stephens), the most predominant pest in the Canadian Prairies (Sinha and Wallace 1977; White and Demianyk 1994).

Sinha and Wallace (1966) studied the ecology of an insect-induced hot spot in stored grain. They found that the heating of a grain pocket could not have been initiated by dampness, because the maximum moisture content of the grain was only 12.5% initially. They observed that hot spot initiation was by *Oryzaephilus surinamensis* (L.) which can complete its life cycle in 20 to 40 d and generate maximum heat at 25 to 35°C (Howe 1965). They observed that, although the hot spot was initiated by *O. surinamensis*, it was developed by *C. ferrugineus*. The characteristics of *O. surinamensis* and *C. ferrugineus* which favor the initiation and development of hot spots are: (1) tolerance to high temperatures, (2) ability to survive at low humidities, (3) high intrinsic rates of increase under favorable conditions, (4) ability to breed at high temperatures, and (5) cold hardiness.

Because fungi develop at temperatures lower than for insects, fungi can begin the temperature rise and then *C. ferrugineus* are attracted towards this warm grain (Smith 1983). So a hot spot may be initiated by fungi and developed by *C. ferrugineus*.

2. 1. 4 Controlling hot spots To maintain grain quality and to avoid deterioration of the grain, control of the insect population and fungal growth is important. Fungal growth can be minimized by maintaining low grain moisture contents. The multiplication and activity of stored-grain insects can be decreased by reducing the temperature of the grain mass below 10°C during early fall (Epperly et al. 1987). Grain temperatures can be reduced using an appropriate aeration strategy. Allowing grain to remain cool during spring and summer months minimizes insect problems (Cuperus et al. 1986). If grain temperatures can be lowered to −5°C for 6 wk or −10°C for 4 wk, most insects will be killed (Loschiavo 1984). Moving grain using mechanical augers or pneumatic conveyors effectively controls *C. ferrugineus* adults (White et al. 1987). Mortality of *C. ferrugineus* was 94% when using a mechanical auger for transporting the grain and 100% when using a pneumatic conveyor (White et al. 1987).

2. 2 Biology of *Cryptolestes ferrugineus*

2. 2. 1 Temperature and relative humidity effects *Cryptolestes ferrugineus* have a remarkable ability to thrive in both temperate and humid-tropical climates (Rilett 1949, Loschiavo and Sinha 1965). They can withstand temperatures as low as −15°C for 2 wk (Smith 1966) and their maximum rate of reproduction is 60 times per month at 32 to 35°C (Smith 1959). The survival rate of adult *C. ferrugineus* increases as the temperature increases from −9 to 40°C (Kawamoto et al. 1989b). Eggs of *C. ferrugineus* are tolerant to high temperatures and low relative humidities (Kawamoto et al. 1989c; Smith 1962 and 1963), however, at a relative humidity of 75%, the development rate of eggs decreases as the temperature increases from 27 to 38°C (Kawamoto et al. 1989b). As the relative humidity decreases from 75 to 50%, the development rate of larvae decreases (Hagstrum and Milliken 1988).

2. 2. 2 Population density Population density affects development, oviposition, and mortality rates of *C. ferrugineus* (Smith 1966). At 30°C and 70% relative humidity, daily oviposition in 0.25 g wheat decreases from 6 eggs/female for 1 pair of beetles to 0.8 eggs/female for 64 pairs of beetles. Development time from egg hatching to adult emergence increases from 28 d for isolated individuals to 42 d for an initial crowding level of 32 larvae in 0.25 g wheat. Mortality increases from 6% for isolated larvae to 98% at 64 larvae in 0.25 g wheat (Smith 1966). In summary, as the population increases oviposition decreases whereas development time and mortality increases (Smith 1966).

2. 2. 3 Heat production Heat production by adult *C. ferrugineus* increases exponentially with increasing temperature from 15 to 35°C. Heat production of larvae increases linearly with increasing moisture content and mechanical damage of the wheat (Cofie-Agblor et al. 1996a, 1996c). Heat production rates of larvae range from 0.4 μW/larva for second instar larvae at 30°C and 12% moisture content, to 18 μW/larva for fourth instar larvae at 35°C and 18% moisture content (Cofie-Agblor et al. 1996b). At the optimal condition of 30°C and 70% relative humidity *C. ferrugineus* consume 340 J per beetle during their life time and release maximum heat (White 1995). Heat production rates in wet wheat of 27% and 23%

moisture content increase with time during heating (Zhang et al. 1992). The heat production rate reaches a maximum of 150 mW/kg for 27% moisture content wheat at temperature of 45°C (Zhang et al. 1992).

2. 2. 4 Movement Rusty grain beetles tend to move downward in a grain mass (White and Loschiavo 1986). Rusty grain beetles prefer a high moisture area rather than a low moisture area (Loschiavo 1983). Loschiavo (1983) studied the movement of rusty grain beetles in an experimental setup having 16 to 17% moisture content wheat in the top half of the bulk and 13.4% moisture content in the bottom half. He observed that most of the rusty grain beetles aggregated in the higher moisture grain.

Rusty grain beetles prefer warm to cold areas (Flinn and Hagstrum 1998). Rusty grain beetles are able to locate the warmest area even at the low temperature gradient of 1°C/0.28 m, i.e., 3.7°C/m (Flinn and Hagstrum 1998). In farm grain bins, as the diameter of the grain bins get larger, rusty grain beetles need to move at least 1 m to move towards the warm region (Flinn and Hagstrum 1998). As the temperature gradients move inward slowly over a period of weeks, *C. ferrugineus* would be able to stay ahead of the cold front (Flinn and Hagstrum 1998) and move into the warm centre of the grain bulk..

2. 3 Heat transfer models

2. 3. 1 Introduction Heat transfer models have been developed to predict the temperatures in stored grain. Temperature is one of the critical factors affecting the distribution of insects, mite and fungi in stored grain (Bala et al. 1989). A knowledge of the temperature distribution in stored grain not only helps in identifying active deterioration, but also gives an indication of the potential for deterioration. Various methods such as analytical methods, numerical methods, analogous methods, and experimental methods are available for solving heat conduction problems (Rao 1982, Jayas 1995). Numerical methods are used more frequently than analytical methods for developing heat transfer models because of the following advantages: (1) a general computer program can be written and; (2) precise prediction of temperatures (Segerlind 1984). The evolution of heat transfer models progressed from analytical models to numerical, three-dimensional models (Jayas 1995).

2. 3. 2 Analytical models Converse et al. (1969) developed an analytical model for predicting grain temperatures based on the assumptions that ambient air temperature varied as a periodic function of time and there was no heat source in the stored grain. They concluded that the lag between the changes in the ambient air temperature and the grain temperature increased almost linearly with the distance from the exposed wall and that the diurnal variation in ambient air temperature had little effect on the wheat temperature.

Manbeck and Britton (1988) developed an analytical model for studying the effect of energy input to and energy loss from the wall on surface temperature of a thin-walled metal grain bin. The mean of the temperature declines predicted at the bin wall were from 4 to 8°C h^{-1} that of the observed values on calm days and 1°C h^{-1} that of the observed temperatures on windy days.

2. 3. 3 Numerical models – One-dimensional models The basic assumption in developing one-dimensional models is that the grain temperature is varying in only one direction and that direction depends upon the problem to be solved (Lo et al. 1975).

Yaciuk et al. (1975) developed a one-dimensional, finite difference model and predicted the effect of thermal properties of grain, initial temperature of the grain, geographical location, diameter of the bin, and type of bin-wall material on the grain temperatures. They assumed that the effect on grain temperatures of heat of respiration by the seeds and other organisms in the grain bulk, heat transfer by conduction in the vertical direction, and heat transfer by free convection within the bin were negligible. They simulated the temperature variations only in the radial direction. They observed that if freshly-harvested grain is stored in large bins it must be cooled immediately after storage to avoid insect infestation. Predicted temperatures in the shipping points of Vancouver, Toronto, and Montreal were higher than predicted temperatures in grain growing areas such as Winnipeg. Under Canadian storage conditions, the larger the bin the higher the pests infestation (Yaciuk et al. 1975). Painting galvanized-steel bins white decreased the grain temperatures (Yaciuk et al. 1975).

2. 3. 4 Numerical models - Two-dimensional models The primary advantage of two-dimensional models over one-dimensional models is their increased number of locations at which temperatures can be predicted. Heat transfer by convection was omitted in one-dimensional models. Two-dimensional models, which include the temperature variations in both the radial and vertical directions, improve the accuracy of the predicted grain temperatures (Muir et al. 1980). The best agreement between predicted and measured temperatures can be obtained assuming a convective heat transfer coefficient of 1 W m^{-2} K^{-1} at the top grain surface (Muir et al. 1980). Increasing the number of space increments and decreasing the time intervals will increase the accuracy of the prediction but at the expense of increased computer time. The inclusion of convection currents in the grain bulk will not result in more accurate predictions of temperature (Muir et al. 1980).

Metzger and Muir (1983) extended the finite difference model of Muir et al. (1980) to include forced convective heat transfer in the vertical direction in cylindrical granaries. This model predicted temperature, moisture content, and deterioration of stored grain with an assumption that grain and air passing through it were at near equilibrium conditions of moisture and temperature. Another assumption was that no heat or moisture is generated in the grain bulk. They found that equilibrium condition between grain and air was not a good assumption at airflow rates as high as 9 (L/s)/m^3, however, at 1.9 (L/s)/m^3 predicted and measured temperatures were in good agreement.

Sarker et al. (1991) developed a finite element model with the following assumptions: (1) the heat flow is symmetric around the vertical axis of the bin and (2) no heat generation within the grain. They used a time step of 72 h and the results predicted were in good agreement with the experimental results. This model was used to locate the areas in a grain bulk most vulnerable to insect infestation.

2. 3. 5 Numerical models - Three-dimensional models Temperatures in stored grain bulks are expected to vary in all three directions and hence three-dimensional models represent better the situation and predict temperatures more accurately than two-dimensional and one-dimensional models (Alagusundaram et al. 1990a). Alagusundaram et al. (1990a) developed a finite difference model to predict temperature distribution in the radial, vertical, and circumferential directions of cylindrical bins. The input data for the model are initial grain temperatures, ambient temperatures, solar radiation on a horizontal surface, wind velocities, and thermal properties of grain, air, soil, concrete, and bin wall. Grain temperatures for the north and south facing parts of bins, predicted by this three-dimensional model were distinctly different from those predicted by a two-dimensional, finite difference model (Muir et al. 1980).This difference is because of the variable heating of bin wall due to variable solar radiation in north and south facing parts of the bin. Predicted temperatures were in good agreement with the measured temperatures at 2-m from the center at a height of 2-m above the floor in a 5.56-m diameter bin containing rapeseed to a depth of 2.7-m.

Alagusundaram et al. (1990b) developed a finite element model for both linear and quadratic hexahedron elements with 1, 2, or 3 point Gauss quadrature in each plane. They observed that the model with quadratic elements did not improve the accuracy of prediction, but it took more computer time for execution of the program than with linear elements. The difference between the predicted temperatures by the three-dimensional finite element and finite difference methods were 3 to 8 K and this difference might be due to the inherent properties of the two methods and the differences in the calculation of the solar radiation. A three-dimensional, finite element model is preferable to a three-dimensional, finite difference model because the three-dimensional, finite difference model is unique for a cylindrical grain storage bin with a flat top surface, whereas the three-dimensional, finite element model can be used to predict the grain temperatures in grain bins of any shape (Alagusundaram et al. 1990b).

Based on the three-dimensional model developed by Alagusundaram et al. (1990b), Jayas et al. (1994) studied the effects of bin diameter, grain bulk height, bin wall material, bin shape, and grain turning on grain temperatures for a storage period of 1 yr. They predicted the following conclusions: (1) center temperatures in large diameter bins are warmer than those in small diameter bins, (2) the effect of the grain temperatures at the top and bottom of the grain surface on the centre temperatures decreases as grain bulk height increases, (3) painting a steel bin white maintains lower temperatures than painting with other colors, (4) the shape of the bins has no influence on grain temperatures, and (5) turning grain reduces the center grain temperatures by about 10°C immediately during winter but over a long period of storage, turning has no significant influence on grain temperatures.

2. 4 Aeration models

Aeration is one of the control measures for reducing the multiplication of insect populations in stored grain. Many models have been developed for studying the aeration effect on grain temperatures. Thompson et al. (1971) developed a simulation model for studying various aeration control strategies and determined the safe storage time for chilled storage at high moisture conditions (more than 15%). They incorporated heat of respiration of grain in the heat conduction model. When the ambient air is cold, continuous aeration maintains low grain temperatures (Thompson et al. 1971). Effects on grain temperatures of such control strategies as aeration-recirculation without refrigeration, aeration-recirculation with refrigeration, and aeration-recirculation with refrigeration and time clock are similar. In summary, continuous aeration using mechanical refrigeration will perform better than other control strategies (Thompson et al. 1971).

The uncertainty of the variables used in mathematical models needs to be analyzed to study the importance of the variables. Sinicio et al. (1997) determined the relative importance of several variables, by adding or subtracting fixed uncertainties from that variable, in a simulation model for aeration with uniform and non-uniform airflow distributions. They concluded that the most important variables were the fan temperature rise, the thin-layer wetting equation, and the thin-layer drying equation whereas the ratio of bin diameter to bin height, air resistance to airflow, and equilibrium moisture contents for adsorption and desorption were less important.

2. 5 Biological models for *Cryptolestes ferrugineus*

2. 5. 1 Population dynamics Under Canadian storage conditions, the rusty grain beetle is the major pest associated with heating and hot spots in grain (Cofie-Agblor et al. 1996a). Predicting the population dynamics of rusty grain beetles would help to decide the timing of prevention measures to be taken for *C. ferrugineus* infestations. Usually a population dynamics model consists of three components: (1) developmental rate, (2) oviposition rate, and (3) mortality rate.

Various methods such as birth and death models, deterministic age-dependent models, and stochastic models of population growth are available for numerically simulating the developmental rates, oviposition rates, and mortality rates of eggs, immatures, and adults (Berry 1987). The physical environment has considerable effect on the insect population in grain bins. But the biological models developed for studying population dynamics of rusty grain beetles assume a constant physical environment, which normally does not persist in stored grain (Throne 1995). Another common assumption in most population dynamics models (e.g., Kawamoto et al. 1989a), except the model developed by Flinn et al. (1992), is that there is no immigration or emigration of insects to or from the grain bulk.

Among the physical variables, temperature is the primary variable and controls the initial growth rate and peak density of rusty grain beetles (Kawamoto et al. 1989a). Kawamoto et al. (1989a) simulated the population dynamics of rusty grain beetles at combinations of three constant temperatures (20, 25, and 30°C) and three constant relative humidities (50, 70, and 90%) with an initial density of one newly emerged female and equivalent males per kilogram of wheat. The simulated population of rusty grain beetles reached a peak value of 63,000 insects/kg of wheat at the favorable conditions of 30°C temperature and 90% relative humidity (Kawamoto et al. 1989a). Their maximum population was regulated mainly by the density-dependent mortality of immatures (Kawamoto et al. 1989a). They defined the population by using cohort-structured vectors instead of stage or age-structured vectors because it can simulate a continuous age-distribution. The immature stages from first instar larvae to pupae are grouped together. Also, this model does not include a resource exploitation factor such as oviposition sites and food which would inhibit the population growth in response to an increasing cumulative population density.

Flinn et al. (1992) developed a spatial model describing insect population as a function of the physical-environment. They coupled the population dynamics model of *C. ferrugineus* with a two-dimensional model of bin temperatures (Metzger and Muir 1983). The grain bin was divided into compartments and growth rates of insect population were simulated based on average daily temperatures of each compartment. The insect model assumed a daily immigration rate of 7 adult females per 351 m^3 into the top two horizontal layers and 4 adult females per 351 m^3 into the bottom two horizontal layers. But movement of rusty grain beetles between compartments was not included in the insect model. The model accurately predicted insect density and grain temperatures for most of the bin compartments. Due to convective air movement, temperatures predicted at the center top portion of the grain mass were 8 °C lower than the observed temperatures. At the end of the storage period, the insect population was over predicted at the centre of the grain mass. They concluded that the host specific parasitoid *Cephalonomia waterstoni* (Gahan) might have appeared in the bin and reduced the population.

2. 5. 2 Bio-energetics Campbell and Sinha (1990) developed a simple computer simulation model for studying the bio-energetics during the progress of a *C. ferrugineus* infestation and described the changes in the major biotic, bio-energetic, chemical, and physical variables in a stored-wheat ecosystem. Within two generations after initial introduction, *C. ferrugineus* reaches a peak in numbers and accelerates the deteriorative process in stored wheat by increasing respiration, temperature, fat acidity values (FAV), and reducing grain germination (Campbell and Sinha 1990). Density-dependent fecundity is not an important regulatory mechanism of *C. ferrugineus* population dynamics (Campbell and Sinha 1990, Campbell and Sinha 1978).

2. 5. 3 Generation times Woods et al. (1997) simulated the number of potential generations of rusty grain beetles in wheat stored in granaries for all crop districts in the Prairie Provinces of Canada. They simulated the number of generations each year from 1952 to 1990 using a population dynamics model driven by ecological variables. The initial storage temperature is the most important factor responsible for predicting the number of generations and levels of infestation of *C. ferrugineus* (Woods et al. 1997). They validated the simulation results with historical data on infestations of stored grain for several years for which initial grain temperatures varied from 18 to 37°C and harvest dates varied from 1 August to 20 October. The number of generations of *C. ferrugineus* annually vary from 0.4 to 7 with a mean of 3.7. The earlier the harvests and the higher the grain temperatures, the greater the number of *C. ferrugineus* generations (Woods et al. 1997). The effects of moisture content and natural reservoirs were not included in the model.

2. 5. 4 Control models Aeration, fumigation, and application of chemical protectants are the main methods used to control rusty grain beetles in stored grain. Hagstrum and Flinn (1990) simulated the effects of control measures on the insect population densities and grain temperatures. Early aeration of storages is more effective than aerating at later dates (Hagstrum and Flinn 1990, Flinn and Hagstrum 1990). Each month delay in aeration results in a 4 to 24-fold increase in the density of *C. ferrugineus* because of the longer time available for the initial population to grow (Hagstrum and Flinn 1990). Delaying fumigation reduces the insect density at the end of the storage period because the time available for population growth after fumigation and before the beginning of cooler fall temperatures is reduced (Hagstrum and Flinn 1990). Malathion eliminates rusty grain beetles at all conditions even at 32°C grain temperature and 14% moisture content, the condition at which malathion breaks down rapidly, there is 2,800 times decrease in population (Hagstrum and Flinn 1990).

Aeration, bin size, and latitude of the bin location have considerable effect on populations of rusty grain beetles (Flinn et al. 1997). Flinn et al. (1997) coupled the effects of aeration, bin size, and latitude in a spatial model of *C. ferrugineus* (Flinn et al. 1992) and compared four aeration strategies to control rusty grain beetles. They were: (1) no aeration, (2) manually controlled aeration, (3) automatically controlled aeration starting at harvest, and (4) automatically controlled aeration starting on 1 September. The sooner the grain is cooled, the earlier the growth rate of insect population reduces (Flinn et al. 1997). In unaerated grain, population densities of *C. ferrugineus* are much greater than in aerated grain (Flinn et al. 1997). Manual aeration is better than no aeration but not as good as automatic aeration started at harvest or on 1 September. Automatic aeration (fans turned on when outside air is 10°C lower than average grain temperature) starting at harvest suppressed *C. ferrugineus* population growth better than automatic aeration starting at 1 September (Flinn et al. 1997). When the ambient temperature is decreasing, population growth of *C. ferrugineus* is greater in non-aerated large bins than in small bins because the effects of changes in ambient air temperature will not affect centre grain temperatures and hence the centre of the grain bulk remains warm and optimal for rusty grain beetle multiplication. Population growth of rusty grain beetles was greater in Oklahoma than in Kansas or South Dakota because grain that is harvested in Oklahoma is usually stored 3-4 wk earlier than grain harvested in Kansas or South Dakota. So grain remains warm for a long period before it cools in the fall and remains favorable for insect population growth longer in Oklahoma than in Kansas or South Dakota.

2.6 Ecosystem modelling using an object-oriented approach

Computer models have been developed for studying such processes related to a stored-grain ecosystem as heat transfer, moisture transfer, gas transfer, insect population dynamics, and stored-grain management strategies (Alagusundaram et al. 1990a, Smith and Sokhansanj

1990, Jayas et al. 1988, Kawamoto et al. 1989a, Hagstrum and Flinn 1990). Stored–grain ecosystems have a complex structure because they involve a large number of abiotic and biotic variables and their interactions. Therefore, full-scale experimental studies of a stored-grain ecosystem are expensive and time consuming, and the generalizations needed to predict the variables are difficult to make (Jayas 1995). For studying stored-grain ecosystems thoroughly and with less cost and time, all the processes involved in stored-grain ecosystems have to be modelled together and a comprehensive model needs to be developed (Kawamoto et al. 1990, 1992).

The basic objective of object-oriented modelling is to construct models that represent the interactions between objects rather than the linear sequence of calculations which is usually referred to as procedural programming (Jorgenson 1994). Objects are entities that have self-contained attributes and behaviours. The structure of object-oriented models duplicates the structure of the system being modelled. Object-oriented modelling provides a natural way to approach modelling of complex systems like stored-grain ecosystems. Object-oriented modelling supports such object-oriented traits as data abstraction, encapsulation, inheritance, and polymorphism (Silvert 1993, Liberty 1998).

In the object-oriented approach all the processes involved in stored-grain ecosystems are treated as separate objects that have self-contained attributes and behaviors. The interactions between the processes are modelled as interrelationships between the objects (Jorgenson 1994). Different kinds of interrelationships between objects are: (1) dependency, (2) association, (3) aggregation, and (4) composition (Liberty 1998).

Various features of object-oriented modelling are (Liberty 1998): (1) object-oriented models are simpler to interpret for the modeller and hence can be easily modified, (2) object-oriented programming makes it possible to develop robust programs, programs that are based on the goal that there is no way in which the program will fail, (3) object-oriented programming helps to develop highly extensible and maintainable source code where extensibility refers to the models ability to add new features and maintainability refers to the developer's ability to understand the model which augments an easily-readable computer program, (4) object-oriented programming supports developing reusable source code that yields the possibility for developing a comprehensive model for stored-grain ecosystems, and (5) object-oriented programming supports writing efficient programs, programs that take little memory.

3. OBJECT-ORIENTED METHODOLOGY IN CONSTRUCTING A HOT SPOT MODEL

3.1. Introduction to object-oriented methodology

Object-oriented methodology is the modelling of a system as a collection of discrete objects (Rumbaugh et al. 1998). Object-oriented methodology produces a simple design that is easier to test, maintain, and extend because the objects provide a natural unit of modularity (Rumbaugh et al. 1998). Objects have both attributes and behaviors. Attributes are variables defined for the objects and behaviors are the transformations that can be implemented between or to objects. Constructing models using object-oriented methodology involves three phases: analysis, design, and implementation.

3.2. Object-oriented analysis

3.2.1. Stored-grain ecosystems: A stored-grain ecosystem is complex because of the large number of abiotic, biotic variables, and control measures and their interrelations. Stored-grain ecosystems involve abiotic variables such as temperature, moisture content, and gas concentration; biotic variables such as heat production, and distribution of insects, mites and fungi; and control measures such as aeration, fumigation, insecticide application, and controlled atmosphere storage (Fig. 1). A reliable and extensible model of stored-grain ecosystems can be constructed by using object-oriented methodology. In a stored-grain ecosystem, hot spot development is one of the main processes to be modelled.

Development of hot spots in stored grain consists of the following phases: (1) variability of abiotic parameters such as temperatures, moisture contents, and gas

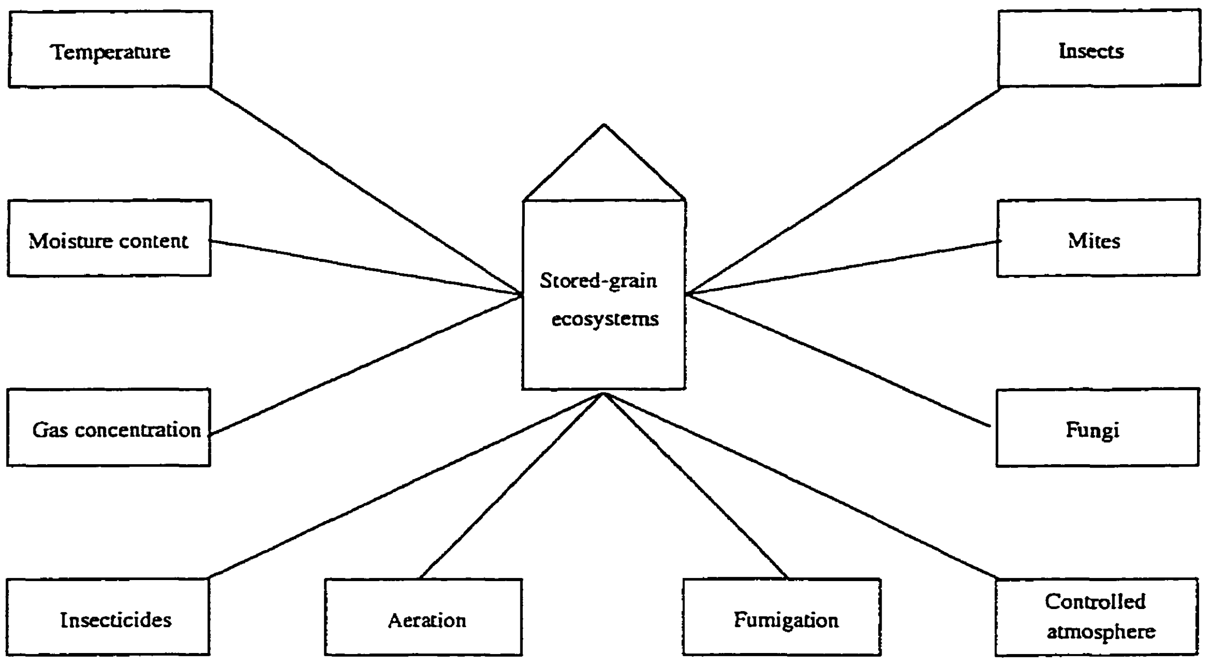


Fig. 1. A schema of variables and control measures in stored-grain ecosystems

concentrations, (2) population dynamics of insects, mites, and fungi, (3) heat production by insects, mites, and fungi, and (4) distribution of insects in stored grain in response to the changes in abiotic parameters.

Population dynamics of fungi have not been modelled because of the difficulty in quantifying fungi. Mites can not penetrate grain bulks extensively and so possibility for development of mite-induced hot spots in stored grain is less (Muir 1997). Many models have been developed for simulating the population dynamics of insects (e.g. Kawamoto et al. 1989a; Flinn et al. 1992) and insects induce hot spots in stored grain (Sinha and Wallace 1966).

The basic concept of the hot spot model was to simulate grain temperatures, the population dynamics of insects, and the possibilities for hot spot occurrences in stored grain for the given initial storage conditions (Fig. 2).

3.2.2. Selection of suitable submodels: Temperature is the most important abiotic variable affecting the multiplication, heat production, and distribution of insects in stored grain (Kawamoto et al. 1989b; Oxley 1948). Temperatures in stored grain bulks are expected to vary in all the three directions. Therefore, a three-dimensional model of heat transfer was used for studying grain temperatures in the hot spot model. The finite element method has been applied to various engineering problems (Rao 1982). Figure 3 shows the discretization of a 6-m diameter bin into 88 linear, two-dimensional elements. A two-dimensional grid of nodes can be transferred into a three-dimensional grid of nodes by using a grid generation program. Material property variations, mixed boundary conditions, and irregularly shaped boundaries can be modelled by applying the finite element method (Alagusundaram 1990b).

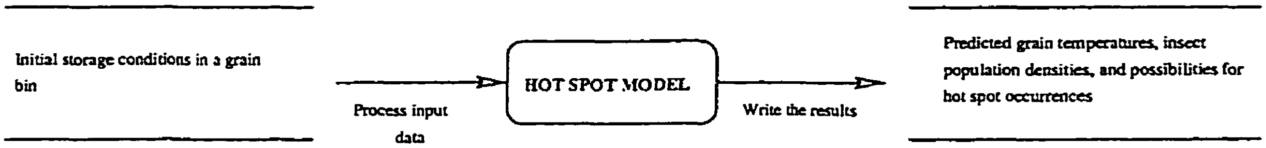


Fig. 2. Basic concept of the hot spot model

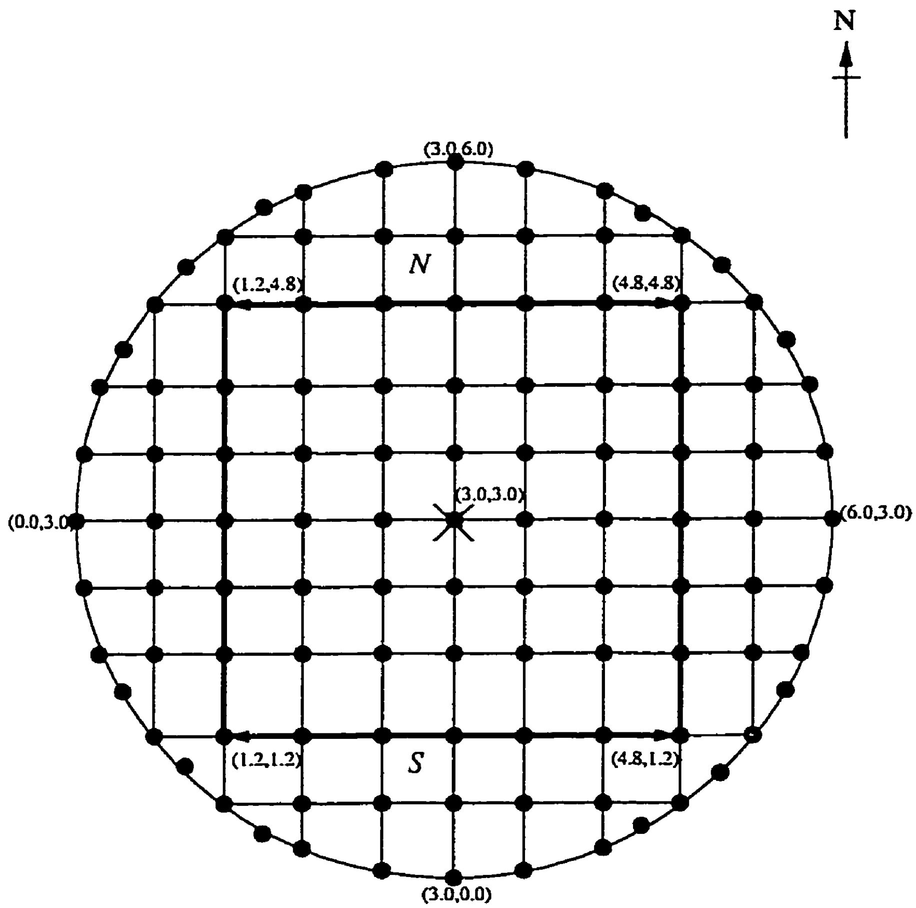


Fig. 3. Discretization of a 6-m diameter bin (Figure shows the plan view at 3-m depth. Figure not to scale)

Each element is 1.2-m thick and represents 350 kg of wheat. Fig. 14 represents the area marked by arrow heads

The finite element method is more suitable to develop heat transfer models than finite difference and analytical methods (Segerlind 1984). Therefore the three-dimensional, finite element model of heat transfer developed by Alagusundaram et al. (1990b) was used in the hot spot model to predict grain temperatures. The heat transfer model involves such calculations as three-dimensional grid generation, boundary conditions, internal heat generation, and solving finite element equations (Fig. 3).

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. (1989a) was chosen because this model was developed based on the results of experiments that were done under Canadian storage conditions. A model of heat production rates of *C. ferrugineus* developed by Cofie-Agblor et al. (1996a) was selected.

Flinn and Hagstrum (1998) conducted experiments to study the effects on 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 movement of insects. Detailed descriptions of the submodels are presented in section 4 of this thesis. The submodels of population dynamics, heat production rate, and movement of *C. ferrugineus* used in the hot spot model were simulated for only wheat bulks. Therefore, the hot spot model in its present form can be used for only wheat bulks.

3.3. Object-oriented design

The main transformations in the submodels, which were selected in the analysis phase, were defined as separate classes. Class is a user-defined type and can have many objects (Farrell 1998, Stroustrup 1997). Inheritance is the process by which an object of a class acquires properties of an object of another class. Multiple inheritance is the process by which an object of a class acquires properties from objects of two or more classes. Two kinds of inheritance are: inheritance of specifications and inheritance of specializations. Inheritance of specifications describes an object that has many specifications whereas inheritance of specializations describes an object that has many specializations. For example, assuming insect population dynamics as a parent class and a class representing the population dynamics of *C. ferrugineus* inherits properties from that parent class, this relation is described as inheritance of specializations. Assuming the classes of heat transfer, heat production, etc. as parent classes and a class representing the insect population dynamics inherits properties from those parent classes, this relation is described as inheritance of specifications.

An object of a class representing a hot spot induced by *C. ferrugineus* needs specifications on heat transfer phenomena occurring in the grain bulk, population dynamics of *C. ferrugineus*, heat production rates of *C. ferrugineus*, and movement of *C. ferrugineus*. An object of a class representing the temperature distributions needs specifications on grid generation, numerical integration, boundary conditions, internal heat generation, and equation solving (Fig. 4). Therefore, the concept of inheritance of specifications best describes the hot spot model.

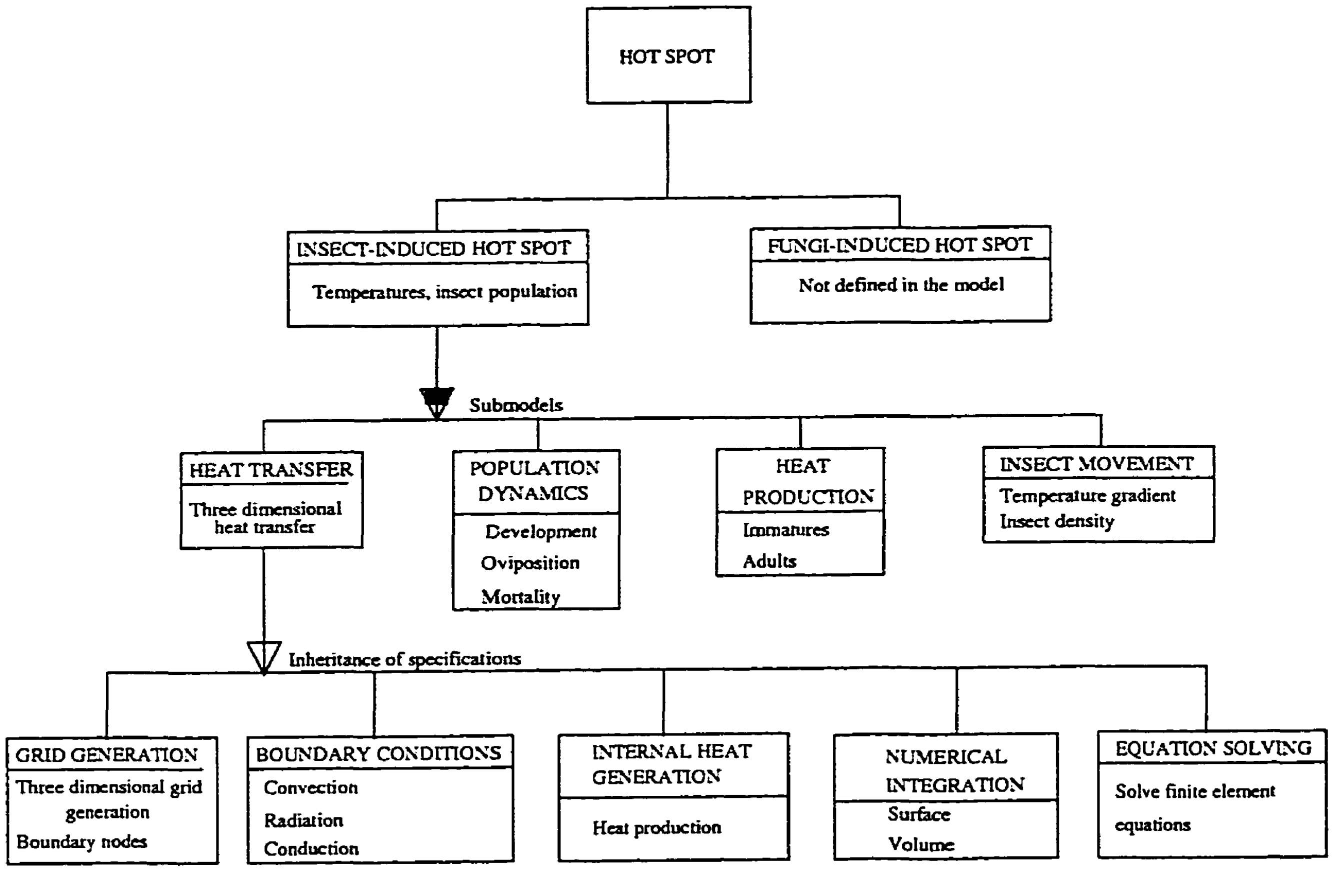


Fig. 4. Object diagram for the hot spot model

The hot spot class (derived class) was the agent class that mediates between the specifications that were defined as separate classes (parent class). The hot spot class calls the necessary transformations from the parent classes in sequence for the stipulated simulation period (Fig. 5). To assist the extension of the hot spot model in the future, submodels of moisture transfer, gas transfer, aeration, and population dynamics of other insect species were declared as dummy classes (Fig. 6). Objects of those classes were not defined in the hot spot model, i.e., these objects were not given attributes or behaviors.

The classes and their specifications in the hot spot model were (Fig. 6): (1) the grid generation class converts two-dimensional nodes to a three-dimensional grid of nodes, (2) the numerical integration class integrates the surface and volume, (3) the boundary condition class calculates soil temperatures, radiation coefficients, and convection coefficients based on the given weather data, (4) the population dynamics class calculates development rates, oviposition rates, mortality rates, and population densities of *C. ferrugineus*, (5) the heat production class determines the internal heat generation based on heat production of *C. ferrugineus*, (6) the movement class simulates the distribution of adult *C. ferrugineus* in response to temperature gradients in the grain bulk, (7) the solution class solves the finite element equations for grain temperatures, (8) the aeration class* determines the changes in grain temperatures during ventilation, (9) the moisture transfer class* determines any changes in moisture contents of the grain bulk, (10) the gas transfer class* determines the gas concentrations throughout the grain bulk, (11) the miscellaneous class* determines the

---

* Classes that are not defined in the hot spot model

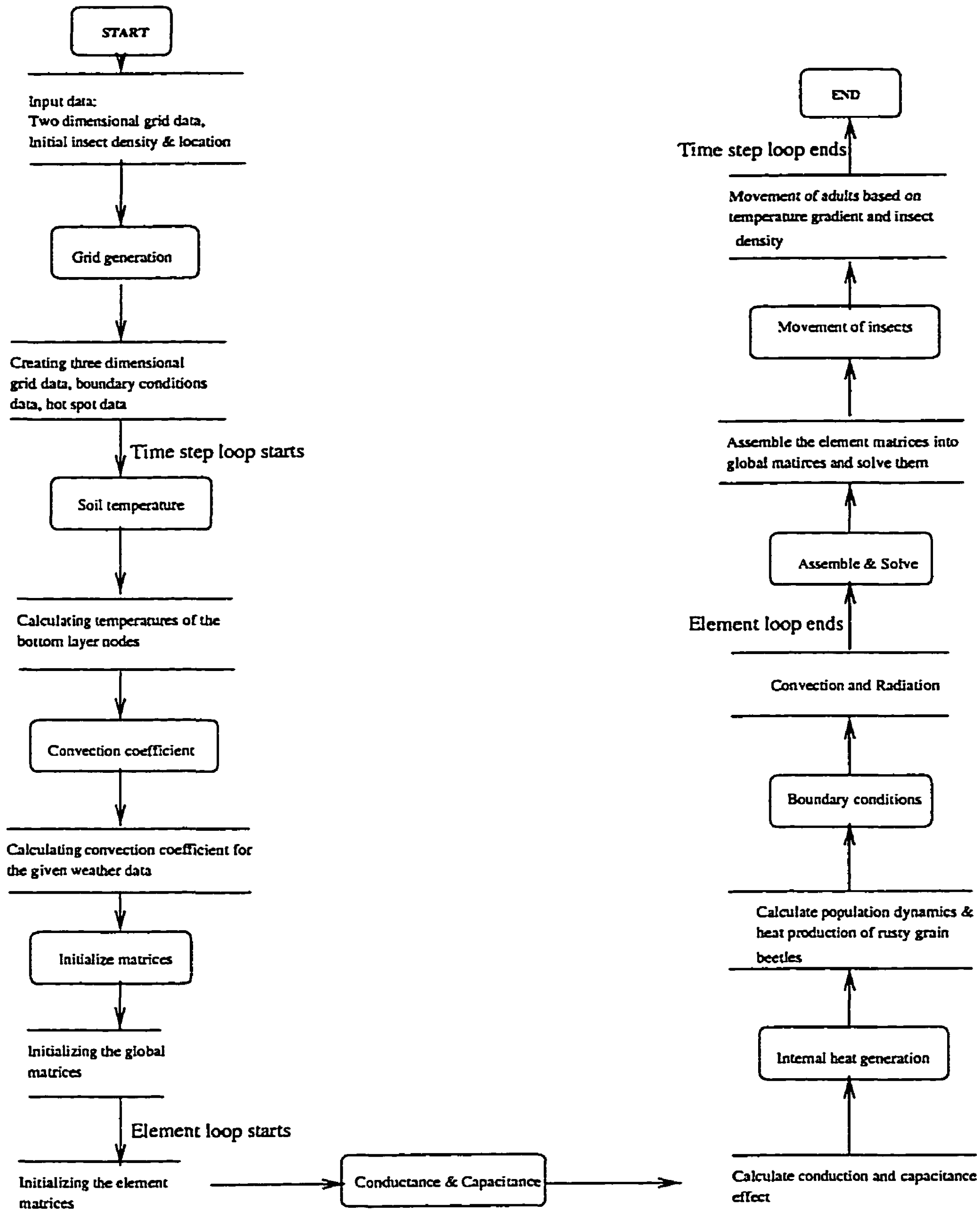


Fig. 5. Data-flow diagram for the hot spot model

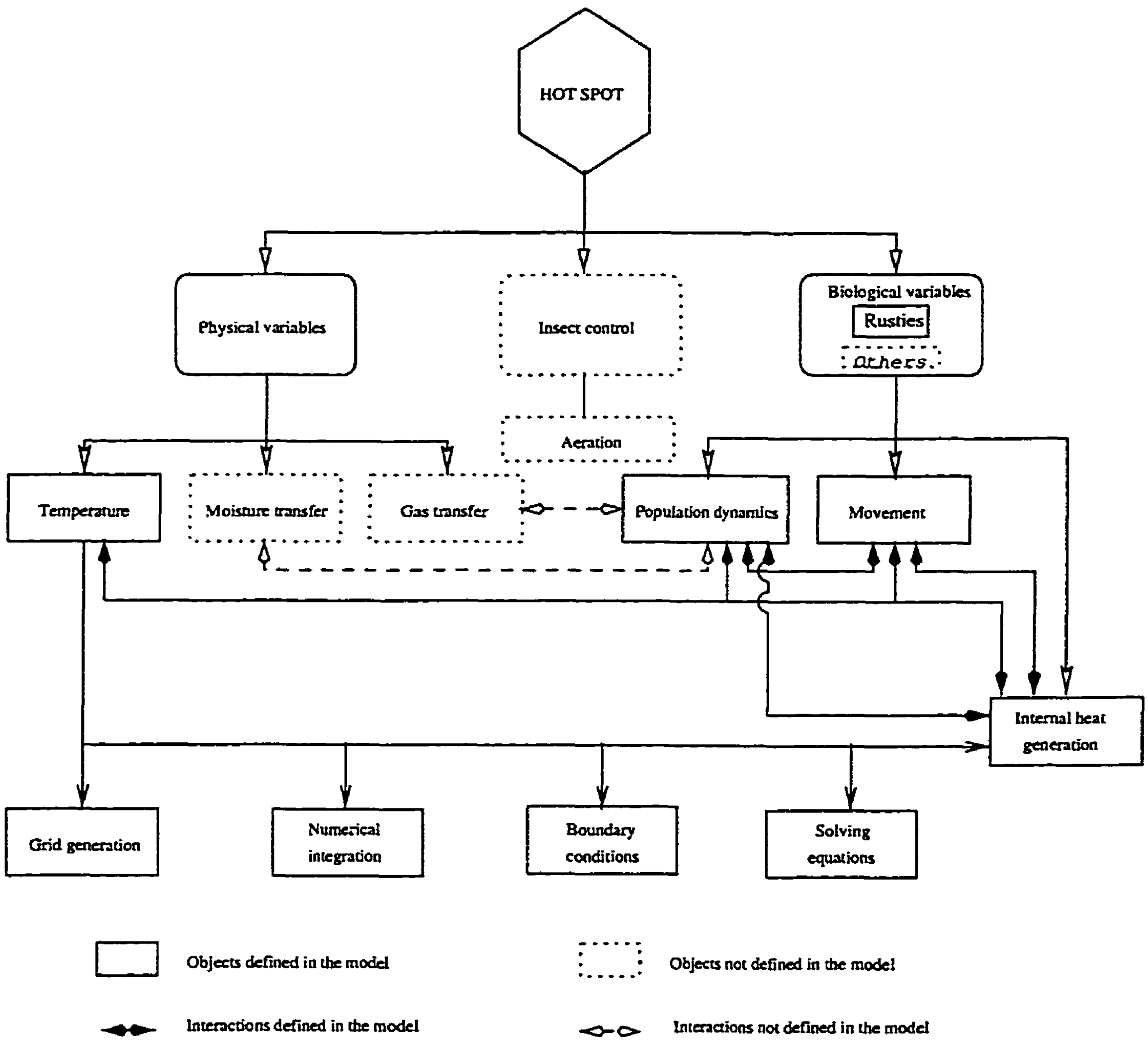


Fig. 6. Architecture of the hot spot model

population density and heat production of insects other than *C. ferrugineus* (for example *Oryzaephilus surinamensis*) that may produce hot spots in stored grain, and (12) the hot spot class inherits the properties of all classes and predicts the possible development of hot spots.

3.4. Object-oriented implementation

Computer programming language C++ supports many object-oriented features and the compilers, editors, and class libraries of C++ are superior to those of other languages (Liberty 1998). Because of its user friendliness, good quality tools, and overall performance of the code, C++ is being widely used to solve object-oriented problems (Rumbaugh et al. 1998).

The three-dimensional, finite-element model of heat transfer (Alagusundaram et al. 1990b), one of the submodels of the hot spot model, was coded in FORTRAN 77 on a main frame system (AMDAHL 5870, University of Manitoba, Canada). The population dynamics model of *C. ferrugineus* developed by Kawamoto et al. (1989a) was coded in VAX FORTRAN (Agriculture Canada, Winnipeg, Canada). For easy extensibility, both of these submodels were restructured in C++ and the submodels of heat production of *C. ferrugineus* and movement of *C. ferrugineus* were written in C++. As the hot spot model was written in C++, it is easy to implement the model as a stand-alone application or possibly as an application embedded in the World Wide Web.

The hot spot model was developed in a Unix (Sun Solaris) operating system (University of Manitoba, Canada) and a C++ compiler, g++, was used to compile the source code. With only a few modifications, the hot spot model could be implemented in a Windows operating system (VC++). Despite the current implementation, future implementation in the computer programming language, JAVA, would give the hot spot model a distinct feature of system-independency. A detailed description of the objects, their attributes, and behaviors are included in the Appendices A and B of this thesis.

4. DEVELOPMENT OF THE HOT SPOT MODEL

4.1 Introduction

Hot spot development in stored grain depends mainly on such factors as temperature, insect population, heat production rates of insects, and movement of insects. To solve specific problems in stored grain ecosystems, research studies have been done separately on heat transfer, population dynamics of *C. ferrugineus*, heat production rate of *C. ferrugineus*, and movement of *C. ferrugineus*. Heat transfer models (Converse et al. 1969, Muir et al. 1980, Metzger and Muir 1983, Sarker and Otto 1991, Alagusundaram et al. 1990a, 1990b, Jayas et al. 1994) were developed for predicting grain temperatures with the main assumption that the effect of internal heat generation on grain temperatures was negligible, which is unlike to situation prevailing in farm grain bins. The population dynamics model of *C. ferrugineus* assumes there is no movement and the physical environment for multiplication is constant (Kawamoto et al. 1989a). Based on experimental results, models were developed for predicting heat production rates (Cofie-Agblor et al. 1996a) and movement (Flinn and Hagstrum 1998) of *C. ferrugineus*.

A computer model for studying the development of *C. ferrugineus*-induced hot spots in stored grain was developed by combining the separate research works on heat transfer, population dynamics, heat production rates, and movement of *C. ferrugineus* and by incorporating the interactions between them. The hot spot model consist of four submodels: (1) three dimensional, finite element model of heat transfer, (2) population dynamics model of *C. ferrugineus*, (3) heat production rate model of *C. ferrugineus*, and (4) model of movement of *C. ferrugineus* with respect to temperature gradients. This chapter describes each submodel in detail.

4.2 Heat transfer model

4.2.1 Heat conduction equation: The three-dimensional, finite-element model of heat transfer developed by Alagusundaram et al. (1990a) was used in the hot spot model for simulating the grain temperature distributions. Heat transfer in an isotropic solid body was modelled in Cartesian co-ordinates considering heat transfer in all three directions. The heat

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right)+\dot{q}=\rho C \frac{\partial T}{\partial t} \qquad (1)$$

conduction equation used was: Boundary conditions were:

$$T(x,y,z,t) = T_0 \qquad \text{for } t>0 \text{ on S1 (Dirichlet condition)} \qquad (2)$$

$$K_x \frac{\partial T}{\partial x} l_x + K_y \frac{\partial T}{\partial y} l_y + K_z \frac{\partial T}{\partial z} l_z + q_r = 0 \qquad \text{for } t>0 \text{ on } S_2 \text{ (Newmann condition)} \qquad (3)$$

$$K_x \frac{\partial T}{\partial x} l_x + K_y \frac{\partial T}{\partial y} l_y + K_z \frac{\partial T}{\partial z} l_z + h_c(T - T_a) = 0 \qquad \text{for } t>0 \text{ on } S_3 \text{ (Newmann condition)} \qquad (4)$$

The initial condition was:

$$T(x,y,z,t=0) = T_i(x,y,z) \qquad (5)$$

The Eq. 1 to 5 were solved using the variational approach (Segerlind 1984, Rao 1982). The final equation obtained was:

$$[C]\frac{\partial\{T\}}{\partial t} + [K]\{T\} = \{F\} \qquad (6)$$

where:

$$[C] = \int_V \rho c_p [N]^T [N] dV \tag{7}$$

$$[K] = \int_V [B]^T [D][B] dV + \int_{S_3} h_c [N]^T [N] dS_3 \tag{8}$$

$$\{F\} = \int_V [N]^T \dot{q}\, dV - \int_{S_2} [N]^T q_r dS_2 + \int_{S_3} [N]^T h_c T_a dS_3 \tag{9}$$

The time dependent calculation was carried out using the theta family of approximations (Alagusundaram 1989) and the final equation for calculating the nodal temperatures was:

$$\left(\frac{[C]}{\Delta t} + \theta[K]\right)\{T\}_{n+1} = \left(\frac{[C]}{\Delta t} - (1-\theta)[K]\right)\{T\}_n + \left(\theta\{F\}_{n+1} + (1-\theta)\{F\}_n\right) \tag{10}$$

4.2.2 Convective heat transfer: The convective heat transfer coefficient is affected by wind velocity, shape and size of the bin, and the temperature difference between the bin surface and ambient air (Jayas 1995).

Equation 11 was used to calculate the convective heat transfer coefficient, h_c, (Incropera and Dewitt 1996):

$$N_u = 0.3 + \frac{0.62\, R_e^{1/2} P_r^{1/3}}{[1 + (0.4/P_r)^{2/3}]^{1/4}} \left[1 + (R_e/282{,}000)^{5/8}\right]^{4/5} \tag{11}$$

where:

$$\text{Nusselt number, } N_u = \frac{h_c d}{k} \tag{12}$$

$$\text{Reynolds number, } R_e = \frac{\rho v d}{\mu} \tag{13}$$

The convective heat transfer coefficient at the top surface of the grain bulk was assumed to be 1 $W \cdot m^{-2} \cdot K^{-1}$ (Muir et al 1980).

4.2.3 Radiation heat transfer: Net radiant heat flow, q_r, was calculated using the following equation (Duffie and Beckman 1974):

$$q_r = q_f + q_d + q_e + q_s - q_o \tag{14}$$

where:

$$q_e = \sigma \alpha F_{be} T_a^4 \tag{15}$$

$$q_s = \sigma \alpha F_{bs} T_s^4 \tag{16}$$

$$q_o = \sigma \varepsilon \{T_s^e\}^4 \tag{17}$$

The radiation on a vertical surface (H_v) at the end of each hour was calculated using measured values of radiation on a horizontal surface (H):

$$H_v = (2R_b H - 2R_b H_b + H_d + \nu H)/4 \tag{18}$$

where:

$$R_b = \frac{\cos\psi_T}{\cos\psi_z} \tag{19}$$

The angles ψ_T and ψ_Z were calculated using Eq. 20 and 21 (Duffie and Beckman 1974):

$$\begin{aligned}\cos\psi_T = {} & \sin\delta \sin\phi \cos Sh - \sin\delta \cos\phi \sin Sh \cos\gamma + \cos\delta \cos\phi \cos Sh \cos\omega \\ & + \cos\delta \sin\phi \sin Sh \cos\omega \cos\gamma + \cos\delta \sin Sh \sin\omega \sin\gamma\end{aligned} \tag{20}$$

$$\cos\psi_z = \sin\delta \sin\phi + \cos\delta \cos\phi \cos\omega \tag{21}$$

The diffuse component, H_d, was estimated by:

$$H_d = K_p H \tag{22}$$

The beam radiation component, H_b, was calculated as the difference between measured radiation on horizontal surface, H, and the diffuse component, H_d.

The value of K_p was calculated using the relationship between K_T, which is the ratio of measured radiation on horizontal surface (H) to the extra terrestrial radiation (H_o), and K_p (Ruth and Chant 1976):

$$K_P = 0.8710458 + (1.12281 K_T) - \left(7.962557 K_T^{2.5}\right) + \left(6.55845 K_T^{3.5}\right) \tag{24}$$

Extra-terrestrial radiation, H_o was calculated using the following equation:

$$H_o = \frac{24}{\pi} I_{sc}\left[\left(1 + 0.033\cos\frac{360D}{365}\right)\left(\cos\phi\cos\delta\sin\omega_s + \frac{2\omega_s}{360}\sin\phi\sin\delta\right)\right] \tag{25}$$

The addition of diffuse and direct radiation components, ($q_f + q_d$), was calculated by multiplying radiation on a vertical surface (H_v) and shortwave absorptivity (γ).

$$(q_f + q_d) = H_v(\gamma) \tag{26}$$

4.2.4 Soil temperature: The soil temperature profile in the horizontal direction under a bin was approximated to the soil temperature profile in the vertical direction (Muir et al. 1980). The Fourier series provided by Singh (1977) was used to calculate the soil temperature at a depth Z, which was in the model, the distance of the corresponding node from the circumference of the bin.

$$T_{(Z,D)} = a_o + \sum e^{\left\{\sqrt{-\frac{n_s\pi}{365\alpha_s}}Z\right\}}\left[a_n \cos\left(\frac{2n_s\pi D}{365} - \frac{\sqrt{n_s\pi}}{365\alpha_s}Z\right) + b_n \sin\left(\frac{2n_s\pi D}{365} - \frac{\sqrt{n_s\pi}}{365\alpha_s}Z\right)\right] \quad (27)$$

The series was truncated after six terms (Singh 1977). The coefficients were taken from the thesis of Alagusundaram (1989). The effects of soil temperature on temperatures of the bottom layer nodes were calculated for every 24 h using Eq. 27.

4.3 *C. ferrugineus* population dynamics model

4.3.1 Submodels: The model of population dynamics of *C. ferrugineus* (Kawamoto et al. 1989a) consists of three submodels: (1) model of developmental rates, (2) model of oviposition rates, and (3) model of mortality rates. The model was developed using cohort structured vectors without immigration and emigration of insects.

4.3.2. Developmental rate: Developmental rate indicates the number of days required for the completion of a life stage, i.e., from egg to immature stage or from immature to adult stage. Duration of the egg stage was shorter than that of the larval and pupal stages. Therefore, the linear equation for calculating the developmental rate of the egg stage was:

$$R_{egg} = \begin{cases} 0.333 & 35 \leq T_{ave} \\ P_{DE}(T - T_{DE}) & T_{DE} \leq T_{ave} < 35 \\ 0 & T_{ave} < T_{DE} \end{cases} \quad (28)$$

The developmental rate of the immature stage was given by the equation:

$$R_{im}(T_{ave}', W) = P(W)Q(T_{ave}') \quad (29)$$

The modification factor for low relative humidity was calculated using the equation:

$$P(W) = \begin{cases} \exp(-B(W_T - W)) & W < W_T \\ 1 & W \geq W_T \end{cases} \tag{30}$$

The developmental rate at T_{ave}' (K) without the effect of low humidity was given by the equation:

$$Q(T_{ave}') = R\left(\frac{T_{ave}'}{298.2}\right)\left[\frac{f_a(T_{ave}')}{1 + f_L(T_{ave}') + f_H(T_{ave}')}\right] \tag{31}$$

where:

$$f_a(T_{ave}') = \exp\left\{H_a \frac{1}{298.2} - \frac{1}{T_{ave}'}\right\} \tag{32}$$

$$f_L(T_{ave}') = \exp\left\{H_L \frac{1}{T_L'} - \frac{1}{T_{ave}'}\right\} \tag{33}$$

$$f_H(T_{ave}') = \exp\left\{H_H \frac{1}{T_H'} - \frac{1}{T_{ave}'}\right\} \tag{34}$$

The stage of each cohort, i.e., egg or first instar larvae or second instar larvae etc., was identified by calculating each cohort's physiological age.

Physiological age, A, was calculated by the following equation:

$$\frac{da}{dtime} = \begin{cases} T_{ave} - T_{AG} & T_{ave} \geq T_{AG} \\ 0 & T_{ave} < T_{AG} \end{cases} \tag{35}$$

4.3.3. Oviposition rate: Oviposition rate indicates the number of eggs laid by a female per day. The physiological age of insects is determined on the basis of the threshold temperature and the grain temperature for each time step. The number of eggs produced by a female, from day i to day j, whose physiological age advances from A_i to A_j is expressed as follows:

$$G = E_{GG} M(T_{ave}, W, D) \exp\left\{-\left(\frac{A_i}{B}\right)^{c}\right\} - \exp\left\{-\left(\frac{A_j}{B}\right)^{c}\right\} \qquad (36)$$

where:

the modification factor, M was given by the equation:

$$M(T_{ave}, W, D) = \exp(-M_{LH} - M_{DRY} - M_{DEN}) \qquad (37)$$

where:

$$R_{egg} = \begin{cases} P_{ML}(T_{ML} - T_{ave}) & T_{ave} < T_{ML} \\ 0 & T_{ML} \leq T_{ave} \leq T_{MH} \\ P_{MH}(T_{ave} - T_{MH}) & T_{ave} > T_{MH} \end{cases} \qquad (38)$$

$$M_{DRY} = \begin{cases} 0 & T_{ave} \leq T_{MDRY} \\ P_{MDRY}(100 - W)(T_{ave} - T_{MDRY}) & T_{ave} > T_{MDRY} \end{cases} \qquad (39)$$

$$M_{DEN} = \begin{cases} 0 & N_{ad} \leq 1 \\ P_{MDEN} \log(N_{ad}) & N_{ad} > 1 \end{cases} \qquad (40)$$

4.3.4. Mortality rate: The basic mortality equation for calculating the change in insect density from day i to day j was:

$$N_j = N_i \exp\{-U(j - i)\} \qquad (41)$$

The instantaneous mortality rate, U was calculated by the following equation:

$$U = U_B + U_L + U_{DRY} + U_{DEN} \qquad (42)$$

Egg mortality rate was calculated using the following equation:

$$U_{EGG} = U_{EGG,B} + U_L + U_{EGG,H} + U_{EGG,DRY} \qquad (43)$$

where:

$$U_{EGG,B} = 0.015 \qquad (44)$$

$$U_{EGG,H} = \begin{cases} 0 & T_{ave} \leq T_{UEH} \\ P_{UEH}(T_{ave} - T_{UEH}) & T_{ave} > T_{UEH} \end{cases} \tag{45}$$

$$U_{EGG,DRY} = \begin{cases} 0 & W \geq 50 \\ P_{UEDR}(50 - W) & W < 50 \end{cases} \tag{46}$$

Immature mortality rate was calculated using the following equation:

$$U_{IMM} = U_{IMM,B} + U_L + U_{IMM,H} + U_{IMM,DRY} + U_{IMM,DEN} \tag{47}$$

where:

$$U_{IMM} = 0.005 \tag{48}$$

$$U_{IMM,H} = \begin{cases} 0 & T_{ave} \leq T_{UIH} \\ P_{UIH}(T_{ave} - T_{UIH}) & T_{ave} > T_{UIH} \end{cases} \tag{49}$$

$$U_{IMM,DRY} = \begin{cases} 0 & W \geq 50 \\ P_{UIDR}(50 - W) & W < 50 \end{cases} \tag{50}$$

$$U_{IMM,DEN} = \begin{cases} 0 & T_{ave} \leq 15 \\ P_{UIDEN}N_{IMM} & T_{ave} > 15 \end{cases} \tag{51}$$

Adult mortality rate was explained by the cumulative thermal stress which is a function of absolute temperature (T_{ave}').

Cumulative thermal stress was calculated using the equation:

$$\frac{dS}{dtime} = \exp\left[P_{SLA} + \frac{P_{SLB}}{T_{ave}'}\right] + \exp\left[P_{SHA} + \frac{P_{SHB}}{T_{ave}'}\right] \tag{52}$$

The density of an adult cohort whose stress increases from S_i to S_j was denoted as:

$$N_j = N_i \exp(S_i^{C} - S_j^{C}) \tag{53}$$

Mortality rates at low temperatures was determined by the following equation:

$$U_L = \begin{cases} 0 & T_{ave} \geq 5 \\ 0.02 & T_{ave} < 5 \end{cases} \tag{54}$$

4.4. Heat production rates of *C. ferrugineus*

Heat production rates of *C. ferrugineus* are one of the main factors for determining the internal heat generation in stored grain. Throughout this thesis, the heat production rates represent the heat production rates of *C. ferrugineus* unless otherwise specified. Because metabolic activities of eggs are probably not significant, heat production rates of the egg stage were assumed to be zero. No research has been done on the heat production rates of first instar larvae. Hence, it was assumed that increase in heat production rate from egg to second instar larvae is linear and the heat production rate of first instar larvae was equal to half of that of second instar larvae.

Generally the heat production rate increases with increasing grain temperature and with increasing grain moisture content (Cofie-Agblor et al. 1996). Heat production rates of different larval instars at grain temperatures from 20 to 35°C in wheat with 20% broken kernels were determined by the following equations (Cofie-Agblor et al. 1996):

(1) for the second instar larvae at 15 and 18% moisture content (wet mass basis):

$$h_{l2} = \exp(-4.759 + 0.037M_c + 0.291T_{ave} - 0.003T_{ave}^{2}) \tag{55}$$

(2) for the third instar larvae:

$$h_{l3} = \begin{cases} -7.187 + 0.451T_{ave}', \text{m.c.} = 12\% \\ -8.985 + 0.582T_{ave}', \text{m.c.} = 15\% \\ -10.968 + 0.667T_{ave}', \text{m.c.} = 18\% \end{cases} \quad (56)$$

(3) for the fourth instar larvae:

$$h_{l4} = \exp(-2.832 + 0.039M_c + 0.243T_{ave} - 0.003T_{ave}^2) \quad (57)$$

No research work has been done on the heat production rate of the pupa stage. The heat production rate of the pupa stage was assumed equal to that of fourth instar larvae. Heat production rates of adult *C. ferrugineus* at 15 to 35°C in 20% broken wheat kernels were determined by the following equation (Cofie-Agblor et al. 1996):

$$h_p = \exp(-3.969 + 0.065M_c + T_{ave}^{0.499}) \quad (58)$$

Equations for heat production rates of adult *C. ferrugineus* at 15 to 35°C in 10% broken wheat kernels and sound wheat were derived using experimental results of Cofie-Agblor et al. (1996):

$$h_p = \exp(-4.177 + 0.07328M_c + T_{ave}^{0.4991}) \text{ for 10\% broken wheat kernels} \quad (59)$$

$$h_p = \exp(-5.267 + 0.1027M_c + T_{ave}^{0.5131}) \text{ for sound wheat} \quad (60)$$

Heat production at grain temperatures higher than 35°C was assumed to be equal to that at 35°C.

4.5. Movement of *C. ferrugineus*

The general tendency of *C. ferrugineus* is to move downward in a grain bulk (White 1995). Because temperature is the main factor determining the rate of *C. ferrugineus* multiplication, the movement of *C. ferrugineus* was assumed to be mainly affected by temperature.

Cryptolestes ferrugineus move from cooler to warmer grain even at the low temperature gradient level of 1°C/0.27-m, i.e., 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. The number of insects moving from an element to an adjacent element, which was at higher temperature, was determined by the temperature difference between those two elements.

The movement of insects was based on three aspects: (1) temperature difference prevailing between elements (>1°C), (2) the total adult population of an element being greater than or equal to 1000 adults/kg of wheat, and (3) the temperature of an element being more than 35°C. The number of *C. ferrugineus* that moved to an element was distributed among all adult cohorts of that element existing at the time of movement. For the number of females moving an equal number of males are also moving to an element.

4.6. 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. No research work has been done on the decline of a hot spot in stored grain. It was assumed that the hot spot will spread throughout and spoil the grain bulk. It was assumed that the grain in a hot spot was completely spoiled and further reproduction of insects was not feasible in the hot spot. Also it was assumed that insects would emigrate from and no insects would immigrate to a hot spot.

4.7. Assumptions made for the hot spot model

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

(1) The physical properties of grain throughout the bulk were constant, however, variable properties can be handled by the model after slight modifications.

(2) The effects of moisture content on grain temperatures, *C. ferrugineus* population dynamics, and movement of *C. ferrugineus* were negligible and the moisture content of grain was uniform at 14.5% (wet mass basis).

(3) The effects of gas concentration on *C. ferrugineus* population dynamics and movement of *C. ferrugineus* were negligible. Gas concentration was assumed to be constant, uniform, and equal to ambient.

(4) A minimum of 2 adults were needed for insect multiplication in a grain pocket and it was assumed that sex ratio (females/(males+females)) was 0.57 (Kawamoto et al. 1989a).

(5) The contribution by other insect species, mites, and fungi to internal heat generation in stored grain was negligible.

(6) The effects of physiological age of insects on movement of adult *C. ferrugineus* was negligible.

(7) The variation in heat production rate of insects due to their physiological age was considered negligible.

(8) Heat production rate of a 4 wk old adult and at a density of 2500 insects/200 g wheat (Cofie-Agblor et al. 1996) was a good representative value for the heat production rate of adults in a population of varying densities and physiological ages,

(9) The emigration of insects from a hot spot to the surrounding grain bulk was not determined by the temperature difference because insects were moving from the warmest region in the grain bulk. 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.

(10) The movement of immatures was negligible.

4.8. Input data for the hot spot model

The hot spot model requires the following input data (Appendix C):

(1) Two-dimensional nodal data, elemental data, boundary data, and hot spot data.

(2) Physical properties of grain, air, soil, concrete, and bin wall material.

(3) Hourly ambient temperature, wind velocity, and solar radiation on a horizontal surface for the desired geographical location, start date of the weather and radiation data, and latitude of the geographical location.

(4) Initial grain temperature, percentage of broken kernels in grain (0, 10, or 20%) and diameter of the bin.

(5) Initial insect density (newly emerged females/kg of wheat), initial life-stage of insects (for example: adults, immature, etc.), and initial location of insects (for example: bottom-centre, middle-centre, top-south, etc.) in the grain bulk.

5. MATERIALS AND METHODS

5.1 Materials

Two cylindrical bins made of 40-mm cardboard, 1-m in diameter and 1.2-m tall were used in the experiment to store wheat. Bins were filled with wheat to a depth of 1-m. Wheat used in the experiment was of the cultivar 'Katepwa'. The initial temperature of the grain was 24°C and initial moisture content was 14.5%. The bin wall and bottom surface were insulated with 40-mm thick fibre glass and the tops of the bins were covered with a muslin cloth. The bins were in a laboratory where the ambient temperatures varied from 15 to 24°C. Adult *C. ferrugineus* were reared in wheat at 30°C and 14.5% moisture content.

There were 40 thermocouples in each bin, which was divided into 5 layers, with 8 thermocouples in each layer. In each layer, two thermocouples were located at radius of 0.05-m, two at 0.25-m radius, and four were located at 0.45-m radius. A digital thermometer (Omega, Stamford, CT) was used to measure the temperatures. A grain probe was used to sample the grain bulk. Copper tubes were used as a heat exchanger medium through which hot water was passed to warm the grain.

5.2 Experimental procedure

The bins were filled with wheat in layers. Each layer was 0.2-m deep. Ten thousand adult *C. ferrugineus* were introduced at the centre of the third layer of each bulk during filling. The insects were initially introduced at the centre because the centre of the grain bulk would stay warm for the longest period to encourage insect multiplication. After 16 d of storage date, an additional 5,000 adults were distributed randomly on the top surface of each grain bulk.

Temperatures were measured every 10 d using the digital thermometer. The grain bins were sampled to determine the insect population every month at 0.07 and 0.4-m radius and at 0.25 and 0.75-m depths. After 24 wk of storage, U-shaped, copper tubes were inserted near the centre of the bulks and hot water (approximately 45°C) was passed through the tubes to warm the grain. The tubes were shifted to all regions of the bulk to heat it uniformly. The observed temperatures and insect population were used to assess the reliability of the hot spot model. The temperatures and insect population densities were not simulated during the period of warming the grain because the comparison between the simulated and observed values for that period was not reasonable due to the addition of heat to the grain bulk.

5.3 Simulation procedure

The simulated grain bin was discretized into five layers containing 440 three-dimensional, linear, hexahedron elements (88 elements in each layer, Fig. 3). The bin was filled to a depth of 6-m. Thickness of each layer was 1.2-m. A grid generation program was written to generate three-dimensional grid nodes from two-dimensional grid nodes. Hourly weather data of ambient temperatures, wind velocities, and solar radiation on horizontal surfaces for Winnipeg, Canada (1986-1987) were used in the hot spot model. The hot spot model can 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 m^{-3} (ASAE 1997). The longwave and shortwave emissivities, 0.28 and 0.89 respectively, for galvanized iron were used (Alagusundaram et al. 1990a). The effects of initial insect location and density on grain temperatures were simulated for wheat of initial grain temperature 30°C and moisture content 14.5% in a 6-m diameter bin. For all simulations, the grain bulk height was set to 6-m.

To compare the temperatures and insect densities predicted by the hot spot model and those observed in the experiment, a 1-m diameter by 1 m tall bin was simulated. Because the experiment was conducted in a laboratory, the effect of solar radiation on grain temperatures was not considered in the simulation of the experimental setup. The 1-m tall grain bulk was divided into three layers with each layer of thickness 0.333-m. The bin was discretized into 240 linear, hexahedron elements (80 elements in each layer) of which 32 elements in each layer represented the wheat bulk and the remaining elements represented the cardboard and insulation materials. A constant ambient temperature of 20°C was assumed for the simulation, however, the observed ambient temperatures varied from 14 to 23°C. It was assumed that the adults introduced into the bulk were newly emerged adults and the sex ratio (females/(males+females)) was 0.57. The bottom layer was assumed to be perfectly insulated.

To do a reasonable comparison of the observed and predicted temperatures and insect population densities the following points were considered: (1) Because the grain was warmed up after 24 wk of storage, by passing hot water through two copper tubes inserted vertically in each bin, only the temperatures and insect population observed during the first 24 wk storage period were compared with predicted temperatures. (2) The insect populations and temperatures observed after the first sampling date (13 July 1998) were compared with the predicted values. Based on these considerations, the comparison was done for the storage period from 13 July 1998 to 13 Oct 1998.

5.4 Differences between the hot spot and spatial models

The following are the differences between the hot spot model and the spatial model (Flinn et al. 1992, for details refer to the section 2.5.1 of this thesis):

(1) The hot spot model used a three-dimensional, finite element model of heat transfer which simulates variable heating around the bin wall. The spatial model used a two-dimensional, finite difference model to simulate the grain temperatures in a south-facing sector of a cylindrical bin.

(2) A cohort-structured model of the population dynamics of *C. ferrugineus* developed by Kawamoto et al. (1989a) was used in the hot spot model. On the other hand, a distributed-delay model of the population dynamics of *C. ferrugineus* was used in the spatial model. In the cohort-structured model, a population of insects is guided by cohorts to move insects through the stages and a continuous age distribution was simulated. In the distributed-delay model, a delay process was involved to move the immature insects through the stages and simulate the variation in developmental rates.

(3) In the hot spot model, adult age was designated as physiological age, which is measured in degree-days after emergence of adults. In the spatial model, adult age was determined by a 70-element array. Because physiological age is determined by the grain temperatures, it is more realistic to consider the insect age as physiological age rather than considering a temperature-independent, 70-element array to keep track of age of insects.

(4) The hot spot model includes a feedback from the insect model to the heat transfer model whereas the spatial model does not include the feedback. In the hot spot model, heat production by insects was determined based on the grain temperatures and moisture contents.

(5) In the hot spot model, the movement of adults was determined by the temperature gradients and insect densities in the grain bulk. The current version of the spatial model does not include the movement of insects between compartments.

(6) The hot spot model begins with an initial insect density while the spatial model simulates a daily insect immigration rate. Because of low ambient temperatures prevailing under Canadian storage conditions, *C. ferrugineus* usually do not migrate from one bin to another. Also a daily immigration rate of *C. ferrugineus* has not been measured under Canadian storage conditions. Hence the hot spot model was developed to simulate the effects of grain temperatures on insects introduced initially into the grain bulk.

Temperature distributions and insect densities in an unaerated, 8.5-m diameter bin filled with wheat to a depth of 6-m at Winnipeg, Canada were simulated by both the hot spot and spatial models. In the hot spot model the bin was discretized into five layers containing 440 linear, three-dimensional elements (88 elements in each layer). Mass of wheat in each element was approximately 600-kg. The 6-m tall bulk was divided into 5 layers with each layer of 1.2-m thick. Temperatures were predicted at 109 nodes in the horizontal plane with a total of 654 nodes for the grain bulk. In the spatial model a 8.5-m diameter bin was divided into 16 compartments and there were 77 nodes within the bin. The discretization of the 8.5-m bin by the spatial model was given by Flinn et al. (1992).

To compare the models, the spatial model was modified to simulate the population dynamics of insects introduced at the centre of the bulk (Region 9, refer to Flinn et al. 1992) on the starting date of the simulation. In the hot spot model, insects were introduced at the centre of the grain bulk. The moisture content of the wheat was assumed to be 14.5%. The model comparison was done for two simulation conditions: (1) an initial insect population of 20 adults and an initial grain temperature of 25°C, and (2) an initial insect population of 10,000 adults and an initial grain temperature of 30°C. In the hot spot model, insects were introduced in 8 centre elements, four elements at the 3-m depth and another four elements at the 1.8-m depth, because the location and volume of these elements were equivalent to the centre compartment (Region 9) in the spatial model. Both models used Winnipeg weather data.

6. RESULTS AND DISCUSSION

6. 1 Effect of initial insect densities

The temperature of each element was calculated as the average of its nodal temperatures. The average of the temperatures of the centre elements was calculated and defined as the average centre temperature. The simulated centre temperature of a 6-m diameter bin, which had no insects, decreased to a minimum temperature of 0.5°C in the following summer (Fig. 7). Introducing 600 adults (1 newly emerged 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. 7). By the end of the summer, 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 infestation was not sufficient to increase the grain temperatures to the level favourable for insect multiplication. Also the development and multiplication of these insects stop at temperatures below 17°C even though the adults can survive at these cool temperatures (Fields and White 1997).

A hot spot was simulated at the centre of the bulk when the grain was infested with 1,300 adults (2 newly emerged females/kg of wheat) at the top-centre of the bulk. Due to heat loss from the top surface, temperatures at the top-centre decreased and hence adults moved from the top-centre to the warm centre of the bulk. Therefore, no increase in centre temperature was predicted for the first 2 mo of simulation (Fig. 7). A hot spot developed and a maximum temperature of 39°C was predicted at the centre by the early winter (Fig. 7).

Introducing 6,000 adults (9 newly emerged females/kg of wheat) at the top-centre of the bulk developed a hot spot in the early winter. Because of the higher initial insect

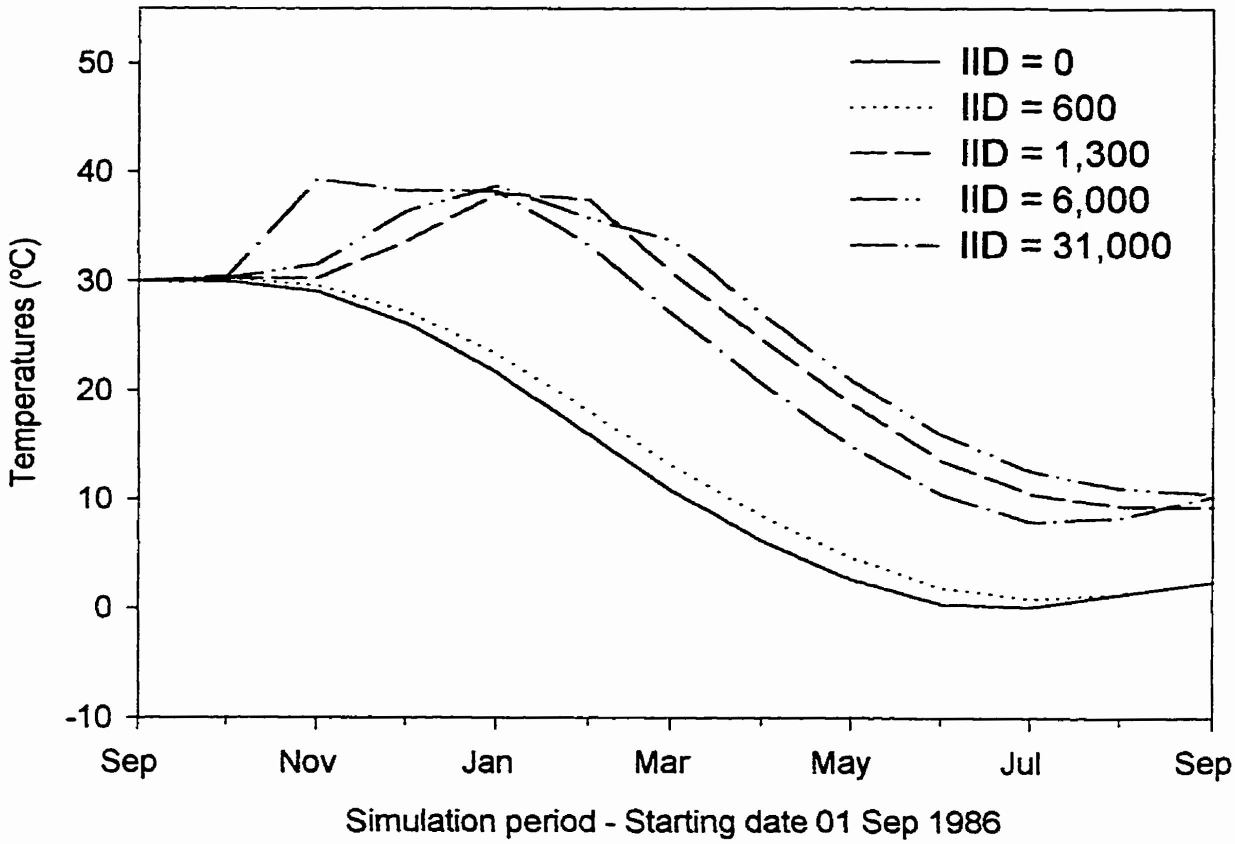


Fig. 7. Predicted average centre temperatures for five initial densities of *C. ferrugineus* (IID - initial insect density, adults introduced in a 350-kg grain pocket) in a 6-m diameter bin filled with wheat to a depth of 6-m at Winnipeg, Canada, the adults were introduced at the top-centre of the grain bulk on 01 Sep 1986

density, more insects moved to the centre of the bulk and heat production increased, which in turn increased centre temperature. For the initial insect density of 31,000 adults (50 newly emerged females/kg of wheat) at the top-centre of the bulk, a hot spot was developed at the centre of the bulk at the end of fall and the centre temperature reached a maximum of 39°C. The higher the initial insect density, the higher and the earlier is the possibility for hot spot occurrence in a 6-m diameter grain bulk.

Because the grain surrounding the hot spot was warm and favourable for insect multiplication, the insects multiplied and then developed hot spots in those regions. 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 wk after reaching the peak temperature. After this transition period, the average centre temperature of the bulk decreased due to the heat losses through the wall and the top surface and there was no addition of heat by insects because they moved out from the centre of the bulk.

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 6,000 adults were introduced. This was because the hot spot occurred earlier in the bulk in which 31,000 adults were introduced. When 6,000 adults were introduced at the top the high initial insect density caused a large proportion of the insects to migrate to the centre of the bulk. Hence the centre temperature of the bulk in which 6,000 adults were introduced remained warmer in the summer than the centre temperature of the bulk in which 1,300 adults were introduced.

Under Winnipeg weather conditions, when a minimum of 600 to 1,300 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. Simulations to predict the effects on hot spot development of initial grain temperatures, bin diameter, and initial insect location were all done for an initial insect density of 6,000 adults.

6. 2 Effect of initial grain temperatures

The higher the initial grain temperature, the higher is the possibility for hot spot occurrences (Fig. 8). At an initial grain temperature of 25°C, the centre temperature decreased to a minimum temperature of 0°C in summer (Fig. 8). *Cryptolestes ferrugineus* are not able to develop and multiply at low temperatures (<17°C) and their heat production is also low at low grain temperatures. 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. No hot spot was simulated in the grain bulk with the initial temperature of 25°C.

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 the early winter. The peak temperature of 39°C was reached in the early winter. A grain temperature of 30°C is the optimal temperature for *C. ferrugineus* to multiply. At an initial grain temperature of 35°C, insects induced a hot spot at the centre of the grain bulk at the end of the fall. The centre temperature remained warm for 8 wk and then decreased.

In summer the centre temperature of the bulk with the initial temperature of 35°C was lower than the centre temperature of the bulk with the initial temperature of 30°C. This is because: (1) the centre temperature of the grain bulk with the initial temperature of 35°C

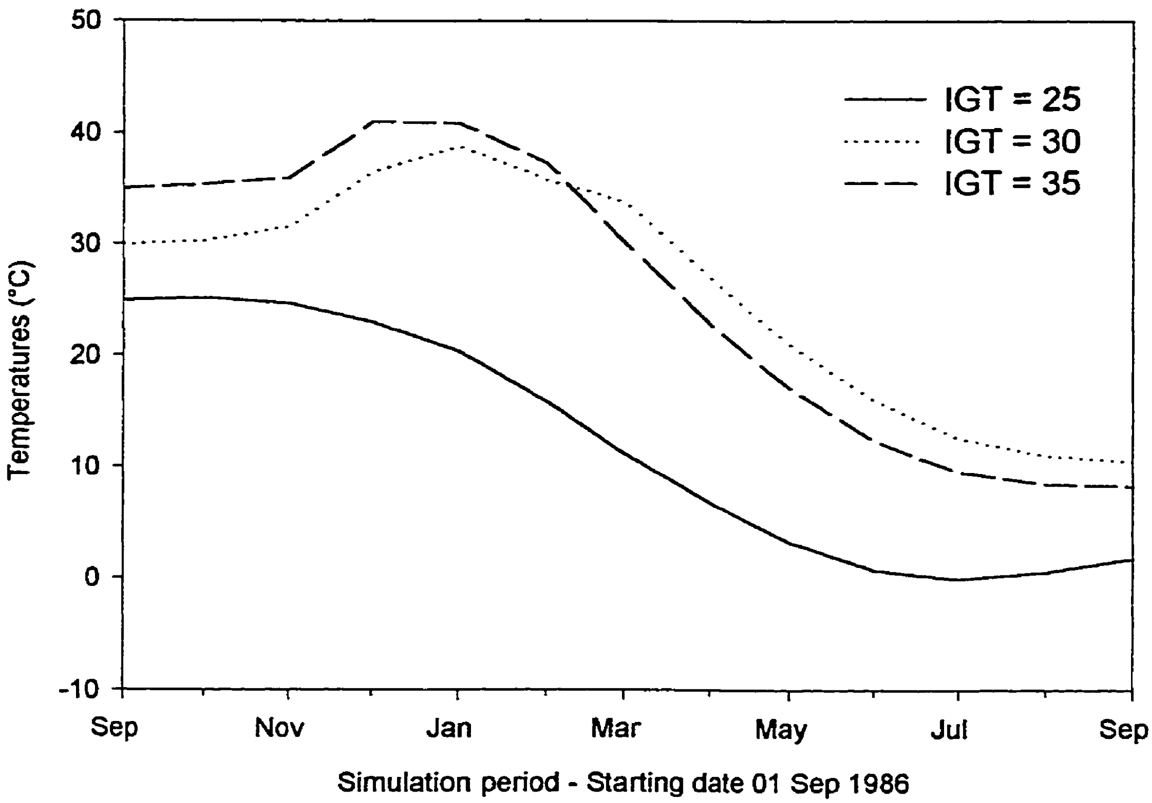


Fig. 8. Predicted average centre temperatures for three initial grain temperatures (IGT, °C) in a 6-m diameter bin filled with wheat to a depth of 6-m at Winnipeg, Canada when 6,000 adult *C. ferrugineus* were introduced at the top-centre of the grain bulk on 01 Sep 1986

reached the peak earlier than the centre temperature of the grain bulk with the initial temperature of 30°C. So, more insects moved out from the centre and developed hot spots in the surrounding bulk earlier. (2) The development and the mortality of insects are affected by the high temperature and hence the rate of increase in population densities was reduced. Hot spots in the surrounding bulk whose initial temperature was 35°C developed and declined earlier than the hot spots in the surrounding bulk whose initial temperature was 30°C.

In summary, at low initial grain temperatures, there is no possibility for hot spot development in stored grain. Cooling the grain to low temperatures is the best method to avoid insect infestation and eliminate hot spot development in stored grain.

6. 3 Effect of bin diameter

The possibility of a hot spot occurrence increased as bin diameter increased (Fig. 9). 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 at the top-centre of a 6-m tall wheat bulk (Size of a grain pocket for various diameter bins: 4-m: 150 kg; 6-m: 350 kg; 8.5-m: 670 kg; 12-m: 1,400 kg). In a 4-m diameter bin no hot spot was simulated for the same simulation condition.

The centre temperature in a 4-m diameter bin reached a minimum of −9°C in the early summer. In a 4-m diameter bin, even though the initial grain temperature was 30°C, which is favourable for *C. ferrugineus* multiplication the heat production by insects could not overcome the heat losses due to the adverse effect of low ambient temperature on the

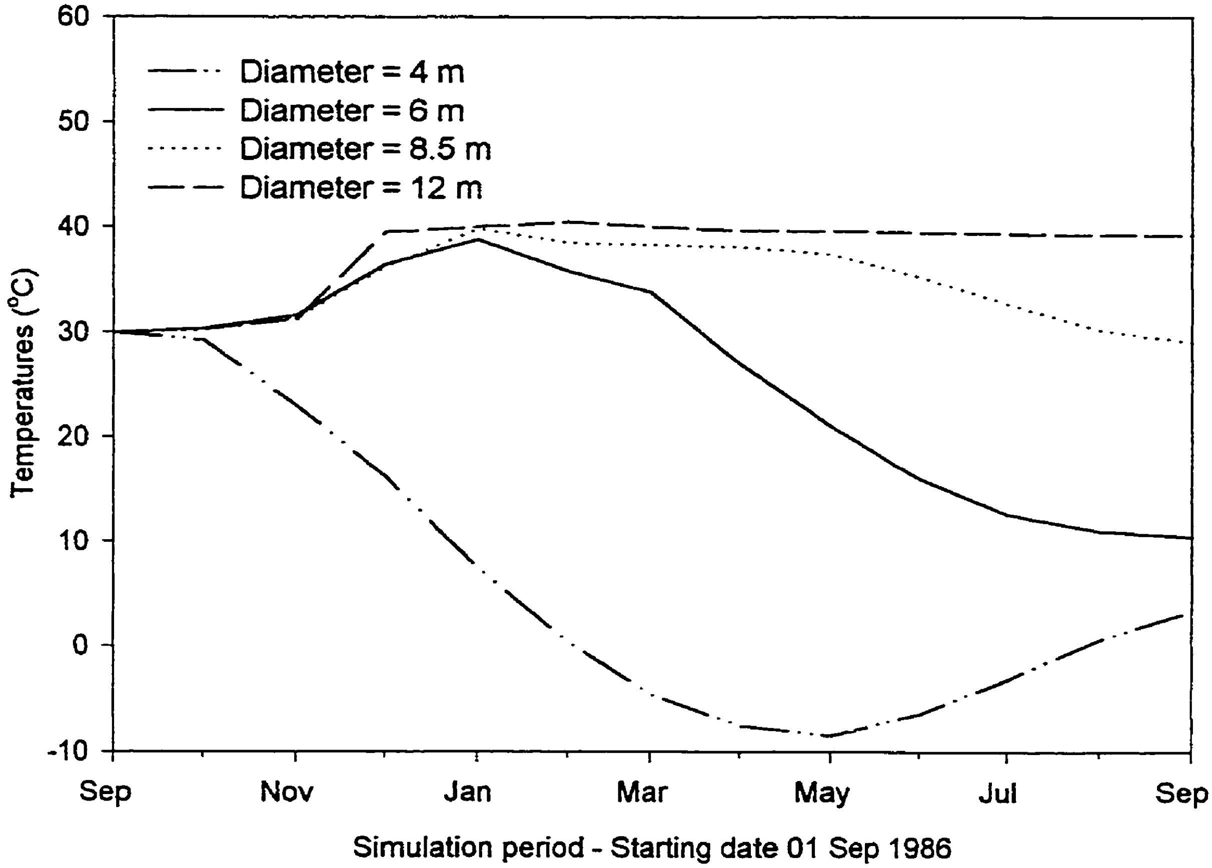


Fig. 9. Predicted average centre temperatures for various diameter bins filled with wheat to a depth of 6-m at Winnipeg, Canada when adult *C. ferrugineus* (9 newly emerged females/kg of wheat, size of a grain pocket: 4-m: 150 kg; 6-m: 350 kg; 8.5-m: 670 kg; 12-m: 1400 kg) were introduced at the top-centre of the grain bulk on 01 Sep 1986

small bulk. Hence the centre temperature of a small diameter bin decreased to a low temperature and was not favourable for insect multiplication. Therefore, there is no possibility for hot spot occurrence in small diameter bins.

In an 8.5-m diameter bin, the centre temperature reached a maximum of 39°C during early winter and it remained above 30°C for the storage period. The centre temperature in a 12-m diameter bin reached a peak of 40°C at the end of fall and remained warm for the storage period. In 8.5 and 12-m diameter bins, which have diameter to height ratios greater than 1, the cooling of the centre of the bulk is mainly influenced by the heat losses through the top grain surface than that from the bin wall. Due to the low thermal diffusivity of wheat, the time lag between the ambient temperatures and the centre temperature increased with increasing bin diameter. Hence in large diameter bins, the centre temperature remained high even though the adults migrated from the centre to the surrounding grain bulk and heat production by insects was decreased.

The centre temperatures in 6-m diameter bins, decreased after they reached the peak temperature due to the heat losses through the bin wall and top grain surface. In a 6-m diameter bulk, the centre temperature was lower in summer than the centre temperature in a 12-m diameter bulk because in a 6-m diameter bulk the cooling of the centre was influenced by heat losses through both the top surface and the wall whereas in a 12-m diameter bulk the cooling of the centre was influenced mainly by the heat losses through the top grain surface.

6. 4 Effect of initial insect locations

6. 4. 1 Depth In a 6-m diameter bin filled with wheat to a depth of 6-m, 6,000 adult *C. ferrugineus* developed hot spots extensively when insects were introduced at 0.6 and 3.0-m depths. But an insect infestation introduced at the 5.4-m depth did not develop an extensive hot spot (Fig. 10) (The term extensive hot spot is used to describe the successful spread of hot spots throughout the grain bulk).

Insects introduced at the centre of the bulk (3.0-m depth) developed hot spots in early winter and average centre temperature reached a peak of 38°C. When the insects were introduced at the top-centre of the grain bulk, they migrated to and multiplied at the centre of the bulk and developed a hot spot. It reached the peak temperature of 39°C in the early winter.

During the late fall, the average centre temperature when insects were introduced at 0.6-m depth was higher than the average centre temperature when insects were introduced at 3.0-m depth. When insects were introduced at the centre of the bulk, due to the high insect density the oviposition rate of the insects was decreased and the mortality rate of the insects was increased. When insects were introduced at the top-centre, the number of insects 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 of insects. During summer, the centre temperature of the bulk in which insects were initially introduced at the centre were higher than the centre temperature of the bulk in which insects were initially introduced at the top-centre. This is because of migration of more insects to the surrounding bulk from the centre of the bulk in

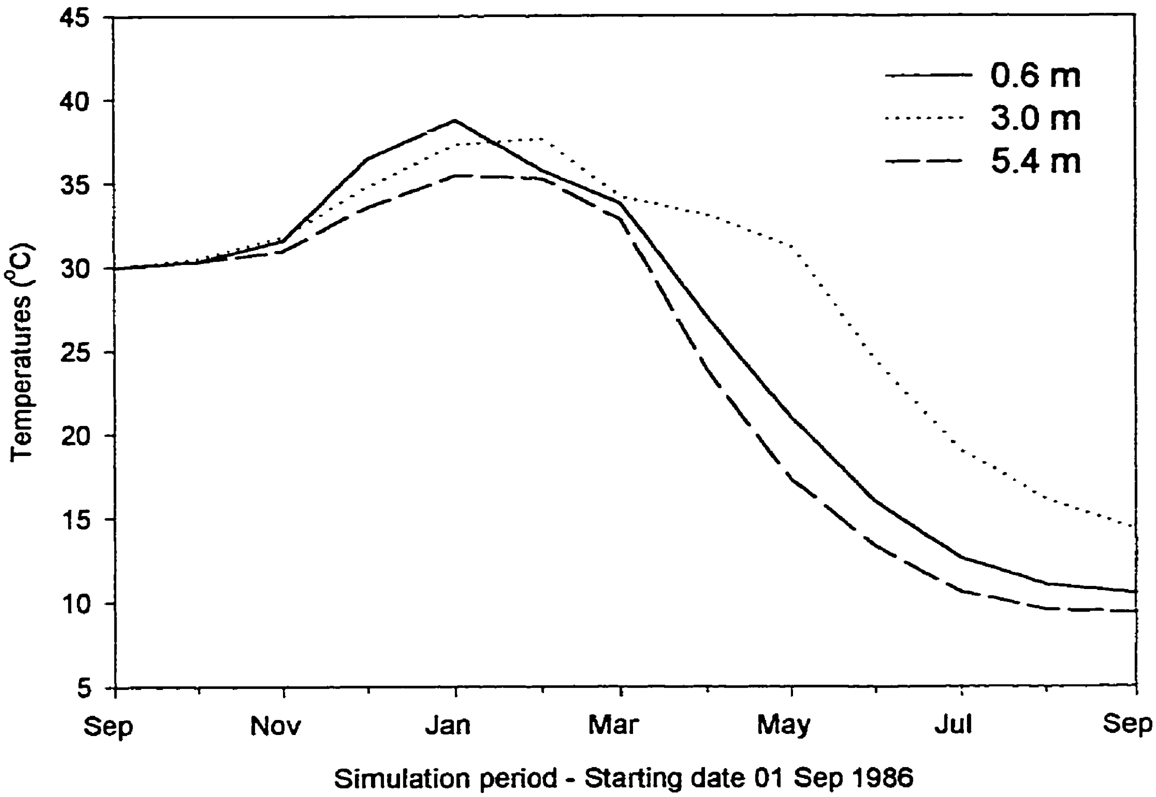


Fig. 10. Predicted average centre temperatures in a 6-m diameter bin filled with wheat to a depth of 6-m at Winnipeg, Canada when 6,000 adult *C. ferrugineus* were introduced at three depths (distance from the top surface of the grain bulk, m) at the centre of the grain bulk on 01 Sep 1986

which insects were initially introduced at the centre (Fig. 10).

When the insects were introduced at the bottom-centre of the bulk (at 5.4-m depth) they developed a hot spot at the centre of the bulk. The centre temperature reached the peak of 35°C in the early winter (Fig. 10). The heat losses through the bottom surface of the bin are less than the heat losses through the top surface. Therefore, the temperature gradient between the centre and the bottom-centre is lower than the temperature gradient between the centre and the top-centre. So fewer insects moved to the centre of the bulk from the bottom-centre. No hot spot was predicted at the bottom-centre of the bulk because of the unfavourable temperatures for insect multiplication at the bottom-centre.

6. 4. 2 Side Figure 11 shows the average centre temperature in a 6-m diameter bin and 6,000 adult *C. ferrugineus* were introduced at: (1) the centre of the bulk, (2) south-east quarter of the bulk at 2.2-m radius and at 0.5-m distance from the horizontal-centre axis along the north-south orientation (Fig. 3, element noted by the letter *S*), (3) north-east quarter of the bulk at 2.2-m radius and at 0.5-m distance from the horizontal-centre axis along north-south orientation (Fig. 3, element noted by the letter *N*).

The three-dimensional heat transfer model, which is a submodel in the hot spot model, simulates the effects of solar radiation on unshaded bin walls. The average centre temperature reached a peak of 39°C in the late winter when insects were introduced along the south side (Fig. 11). When insects were introduced along the north side, the average centre temperature reached a peak of 40°C in winter. At the end of the storage period, the centre temperature of the bulk in which insects were initially introduced along the north side was higher than the centre temperature of the bulk in which insects were initially introduced

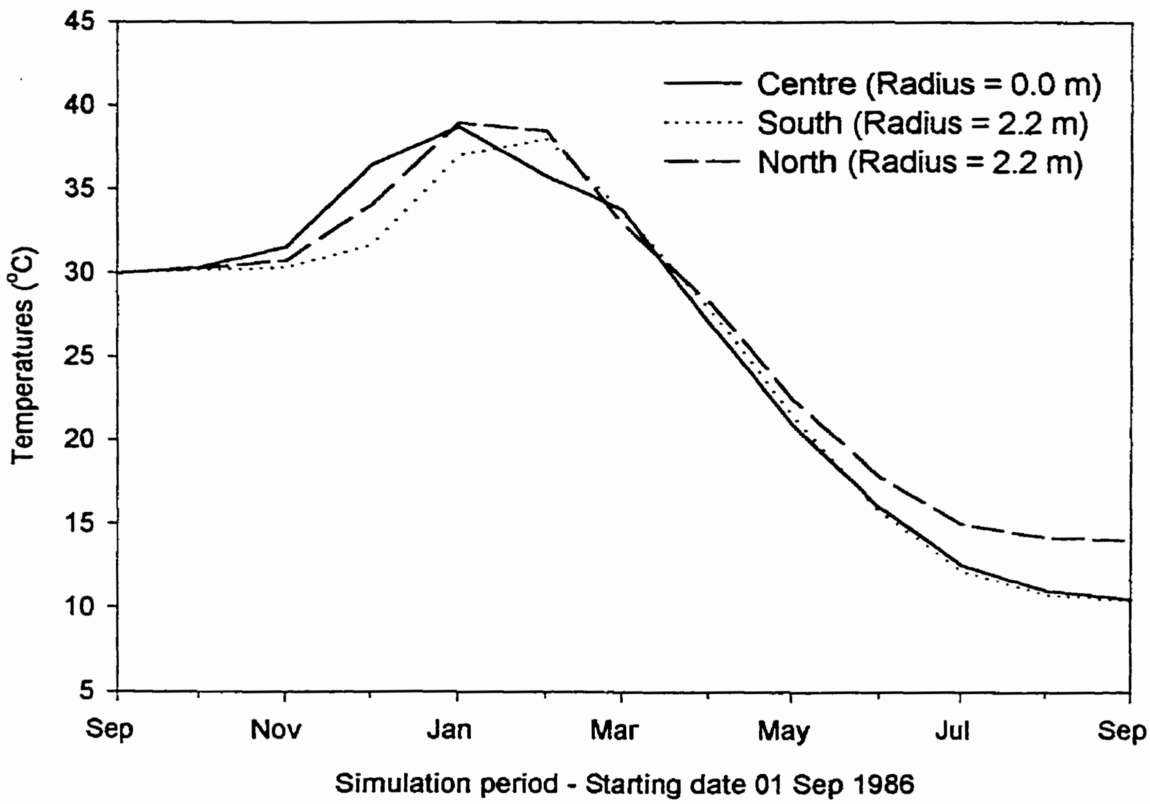


Fig. 11. Predicted average centre temperatures in a 6-m diameter bin filled with wheat to a depth of 6-m at Winnipeg, Canada when 6,000 adult *C. ferrugineus* were introduced at three locations on the top-surface of the grain bulk on 01 Sep 1986

along the south side. This was because the centre of the bulk remained warm till the end of spring when the insects were introduced along the north side.

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 at a 2.2-m radius along the north side of the grain bulk were moved to the centre of the bulk earlier than when they were introduced at 2.2-m radius along the south side of the grain bulk. When the insects were introduced on the south side, due to the optimal condition prevailing at the south side of the bulk, insect population increased in the south side. During winter when grain cooled insects moved to the centre of the bulk.

6. 5 Predicted temperatures and insect densities in a hot spot

During the first 4 wk of storage, adults moved to and multiplied in a 350-kg grain pocket at the centre of the bulk (Fig. 12). Hence, temperatures and adult and immature populations* were increased. The lag between the rise in adult and immature populations was because of the developmental time of eggs into 1st 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. After 8 wk of storage, the grain pocket (350-kg) developed into a hot spot having an adult population of 550 adults/kg and an immature population of 10,200 immatures/kg (Fig. 12). Hot spot temperature spiked from 30°C to 35.6°C.

When the hot spot reaches a temperature of 35°C and higher the adults were assumed to migrate from the hot spot to the surrounding grain. Most of the immatures were assumed

---

*The immature population was the sum of the populations of 1st, 2nd, 3rd, and 4th instar larvae and pupae.

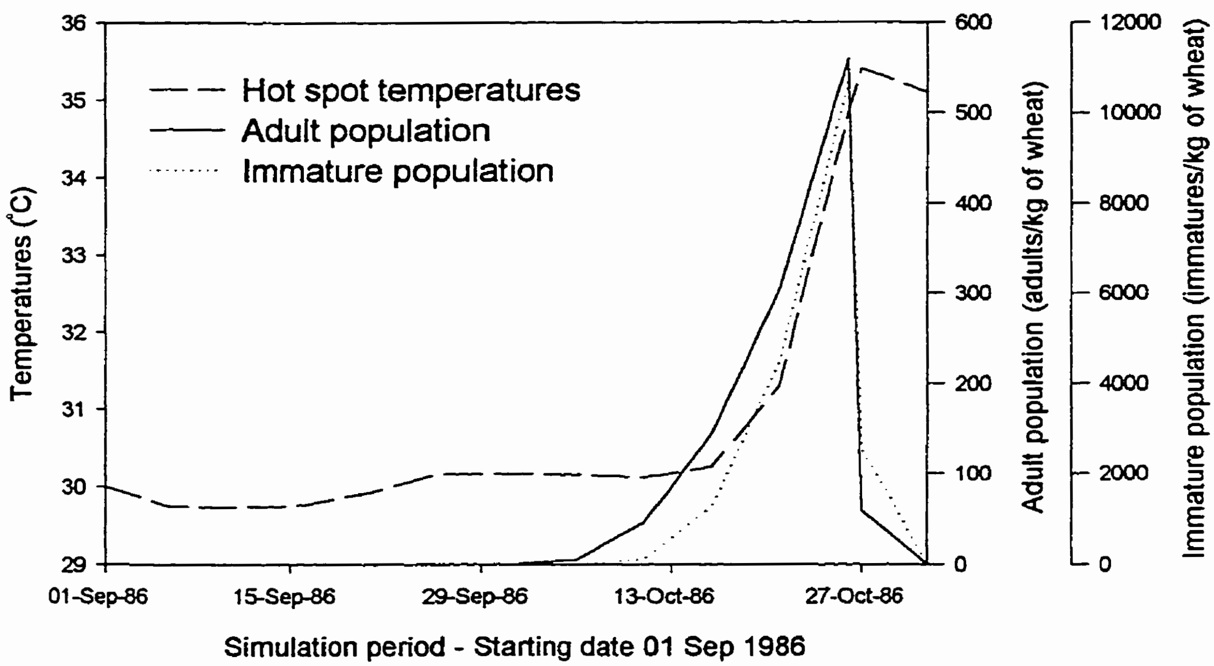


Fig. 12. Predicted population densities of *C. ferrugineus* (insects/kg of wheat in a 350-kg grain pocket) and temperatures (°C) in a hot spot developed at the centre of the grain bulk in a 6-m diameter bin filled with wheat to a depth of 6-m at Winnipeg, Canada when 6,000 adults were introduced at the top-centre of the grain bulk on 01 Sep 1986

to die because of the high temperature and high insect population in the hot spot. Temperatures of the hot spot did not decrease rapidly as the adult and immature population decreased because the thermal diffusivity of wheat is low and because of the heat produced by the adults before their migration to the surrounding grain bulk was simulated (Fig. 12).

Although the adult population in the hot spot decreased after its temperature increased above 35°C, the total adult population in the bin did not decrease. On 27 Oct temperature rose above 35°C and then on 28 Oct, there was a sharp drop in the total immature population in the bin. The rate of increase in the adult population in the bin decreased because of the high immature mortality at the high temperatures and insect density in the hot spot (Fig. 13). At the peak temperature of the hot spot, adult population in the hot spot was 160,000 whereas in the bin it was 200,000. Similarly immature population in the hot spot was 3,100,000 whereas in the bin it was 4,700,000. So, almost 80% of the total adults in the bin were in the hot spot at its peak stage.

6. 6 Predicted distribution of *C. ferrugineus*

Figure 14 shows the response of adult *C. ferrugineus* to the high temperatures of the hot spot (Fig.12) developed at the centre of a 6-m diameter bin. Each element is represented by its geometric centre point. On 27 October 1986, the peak population of 550 adults/kg was reached in the hot spot which was at 35.6°C. Due to the high temperatures the adults migrated from the hot spot to the surrounding grain bulk. The migrated adults heated up much more grain surrounding the hot spot, however, this heated grain was closer to the walls or top-surface or the floor and hence heat losses were high. Hence, in due course on 01 Nov

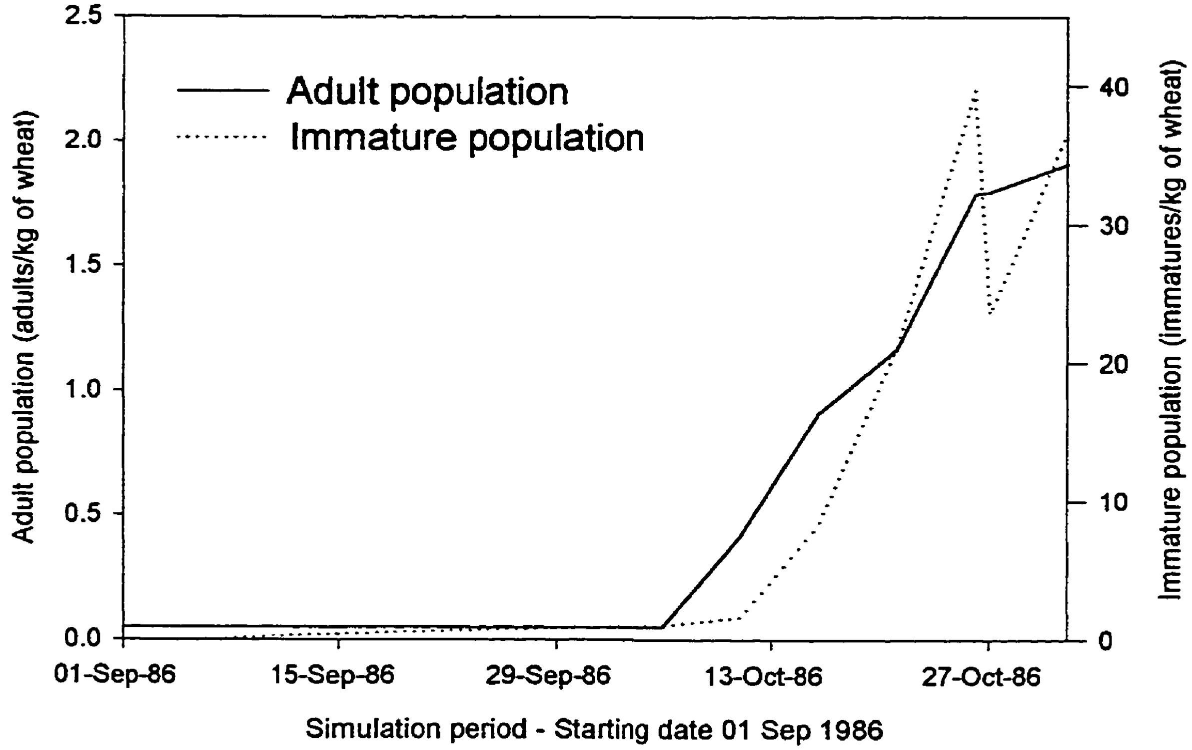
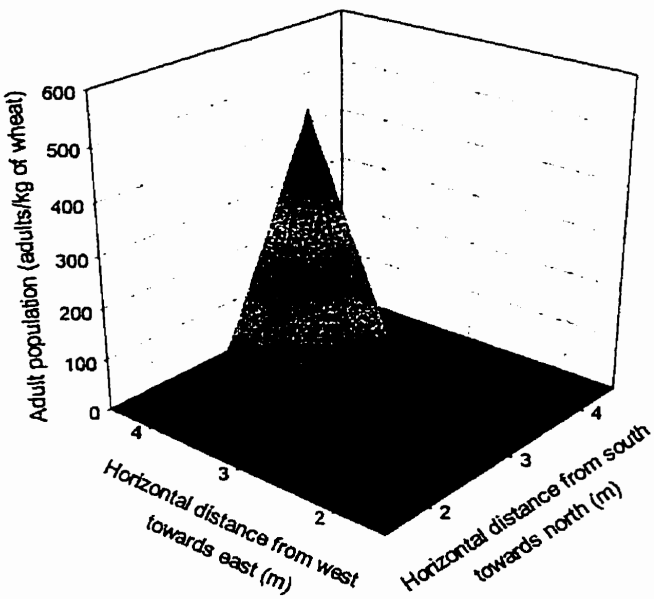


Fig. 13. Predicted population density of *C. ferrugineus* (insects/kg of wheat) in a 6-m diameter bin (total mass of wheat in the bin = 118.4 t) filled with wheat to a depth of 6-m at Winnipeg, Canada when 6,000 adults were introduced at the top-centre of the grain bulk on 01 Sep 1986 (initial grain temperature = 30°C)

27 Oct 1986



01 Nov 1986

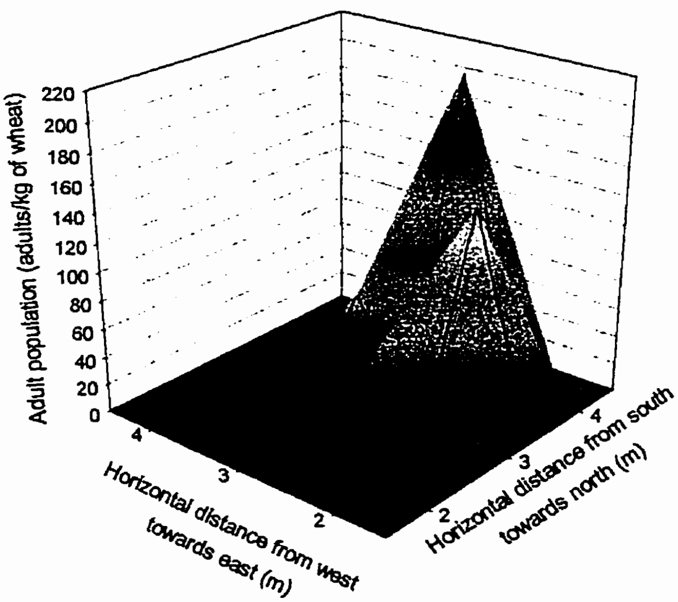


Fig. 14. Predicted distribution of adult *C. ferrugineus* at 3-m depth in a 6-m diameter bin filled with wheat to a depth of 6-m at Winnipeg, Canada when 6,000 adults were introduced at the top-centre of the grain bulk on 01 Sep 1986 (initial grain temperature = 30°C, starting date of simulation = 01 Sep 1986, adult population is given in adults/kg of wheat in a 350-kg grain pocket)

Note: The horizontal plane in this figure represents the area marked by arrow heads in Fig. 3.

1986, insects aggregated in a warm grain pocket (350-kg) near the hot spot location. The grain pocket, in which adults aggregated, was in its initial stage of developing into a hot spot (Fig. 14).

Figure 15 shows the distribution of adults in the wheat bulk at 1.8, 3.0, and 4.2-m depths and at three storage dates. In the Fig. 15 lightly shaded areas represent the lightly infested wheat, i.e., grain pockets with insects, densely shaded areas represent the hot spots, and unshaded areas represent grain pockets without insects. After the hot spot developed, the adult population in hot spots can be zero because adults would migrate from the hot spots.

The first occurrence of a hot spot was detected at the centre of the bulk (at 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. Adults were spread around the centre at all depths. Because of the movement of the adults, the mass of wheat infested by insects increased. Most of the hot spots were predicted in the south side of the bulk because of the high temperatures prevailing in the south side (Fig. 15). The central layer of the bulk (at 3-m depth) was more extensively affected by hot spots than the other layers (at 1.8 and 5.4-m). This is because the centre layer remained warm for favourable multiplication of insects. As hot spots spread throughout the bulk, the mass of infested wheat also increased (Fig. 15).

6. 7 Predicted isotherms

Figure 16 shows the predicted isotherms at the 3-m depth in a 6-m diameter bin. On 01 Nov 1986, when there was only one hot spot, the temperatures at the centre of the bulk were greater than 33°C. Because the hot spot spread around the centre of the bulk, temperatures

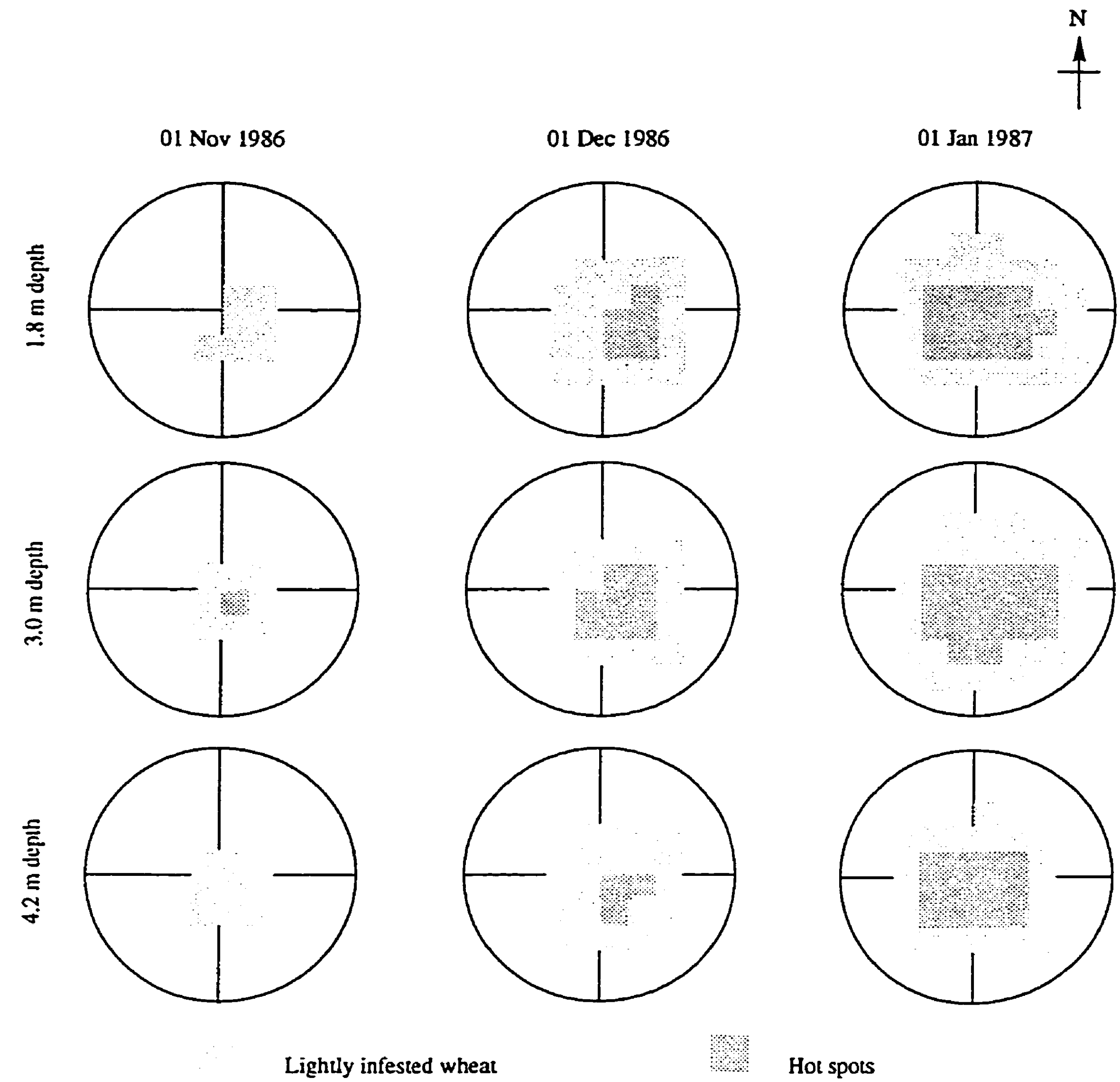


Fig. 15. Predicted distribution of adult rusty grain beetles at three depths in a 6-m diameter bin filled with wheat to a depth of 6-m when 6,000 adults were introduced at the top-centre of the grain bulk on 01 Sep 1986 (initial grain temperature = 30°C, scale: 1 cm = 1.67 m)

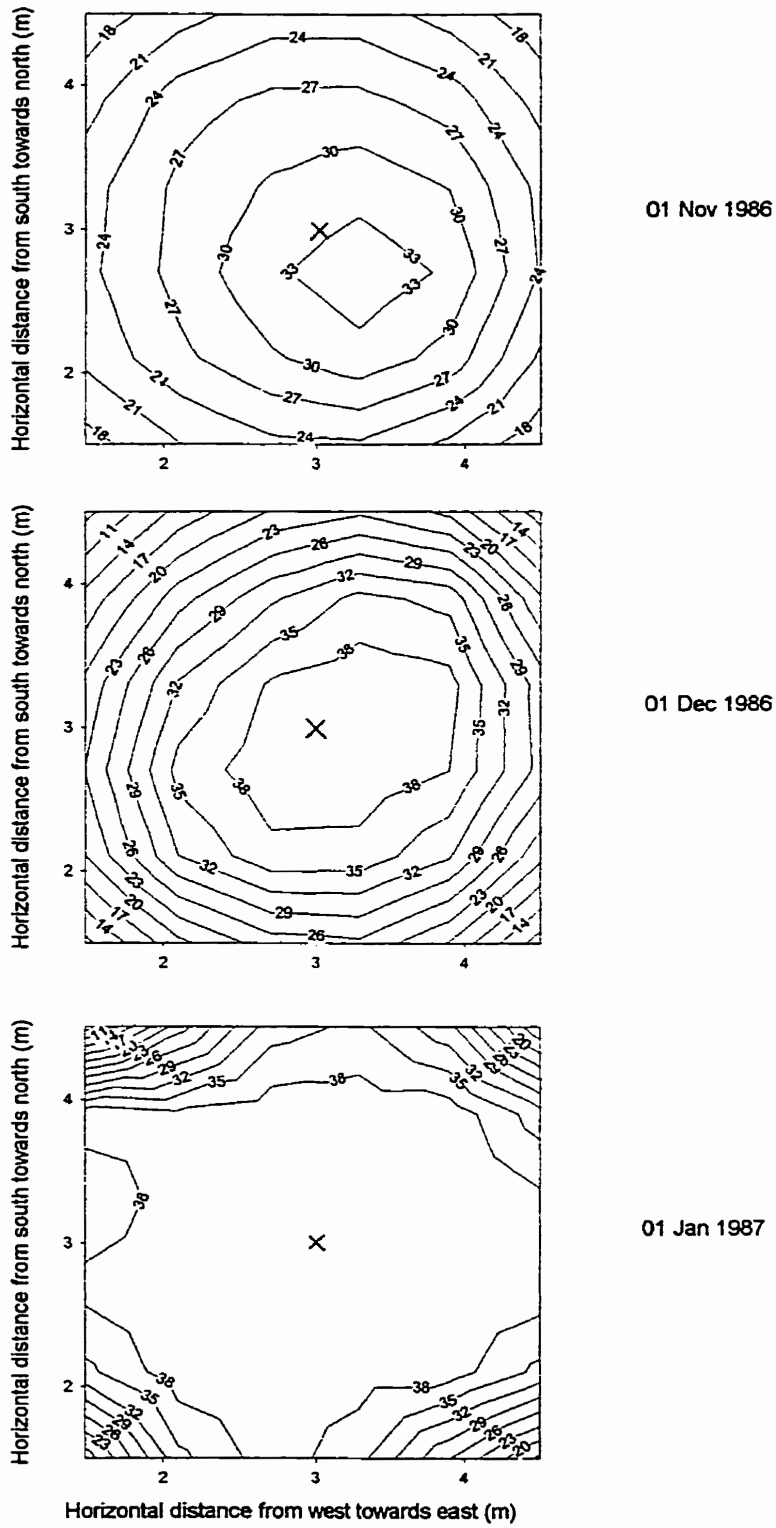


Fig. 16. Predicted isotherms (°C) on various days at 3-m depth in a 6-m diameter bin filled with wheat to a depth of 6-m at Winnipeg, Canada when 6,000 adult *C. ferrugineus* were introduced at the top-centre of the grain bulk on 01 Sep 1986 (initial grain temperature = 30°C, starting date of simulation = 01 Sep 1986)

at the centre increased and reached 38°C on 01 Dec 1986.

On 01 Jan 1987 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. Temperature gradients along the north side of the bulk are higher than temperature gradients along the south side. Due to the migration of insects and heat losses through the wall, temperatures at the centre of the bulk decreased after Jan 1987.

6. 8 Hot spot development in a perfectly insulated bin

Figure 17 shows the predicted temperatures and insect population in a 6-m diameter bin which was perfectly insulated and 6,000 adult *C. ferrugineus* were introduced at the top-centre of the bulk. The purpose of this simulation was to show the effect of heat production by insects on grain temperatures. Because the insects were introduced at the top-centre of the grain bulk, they multiplied in that region and developed a hot spot within 6 wk of storage. Temperatures and insect population increased in the top-centre of the grain bulk more quickly. Once the hot spot reached the peak temperature of 38°C, adults migrated to the surrounding grain bulk. They multiplied and developed a hot spot in the next layer.

The peak adult population in the centre layer (500 adults/kg) was higher than the peak population predicted in the top layer (300 adults/kg). This is because of the continuous migration of adults to the centre of the grain bulk from the surrounding grain bulk. The peak immature population predicted in the top layer (1,700 immatures/kg) was higher than the peak immature population predicted in the centre layer (800 immatures/kg). This is because insects were introduced at the top layer and a longer period was available for initial

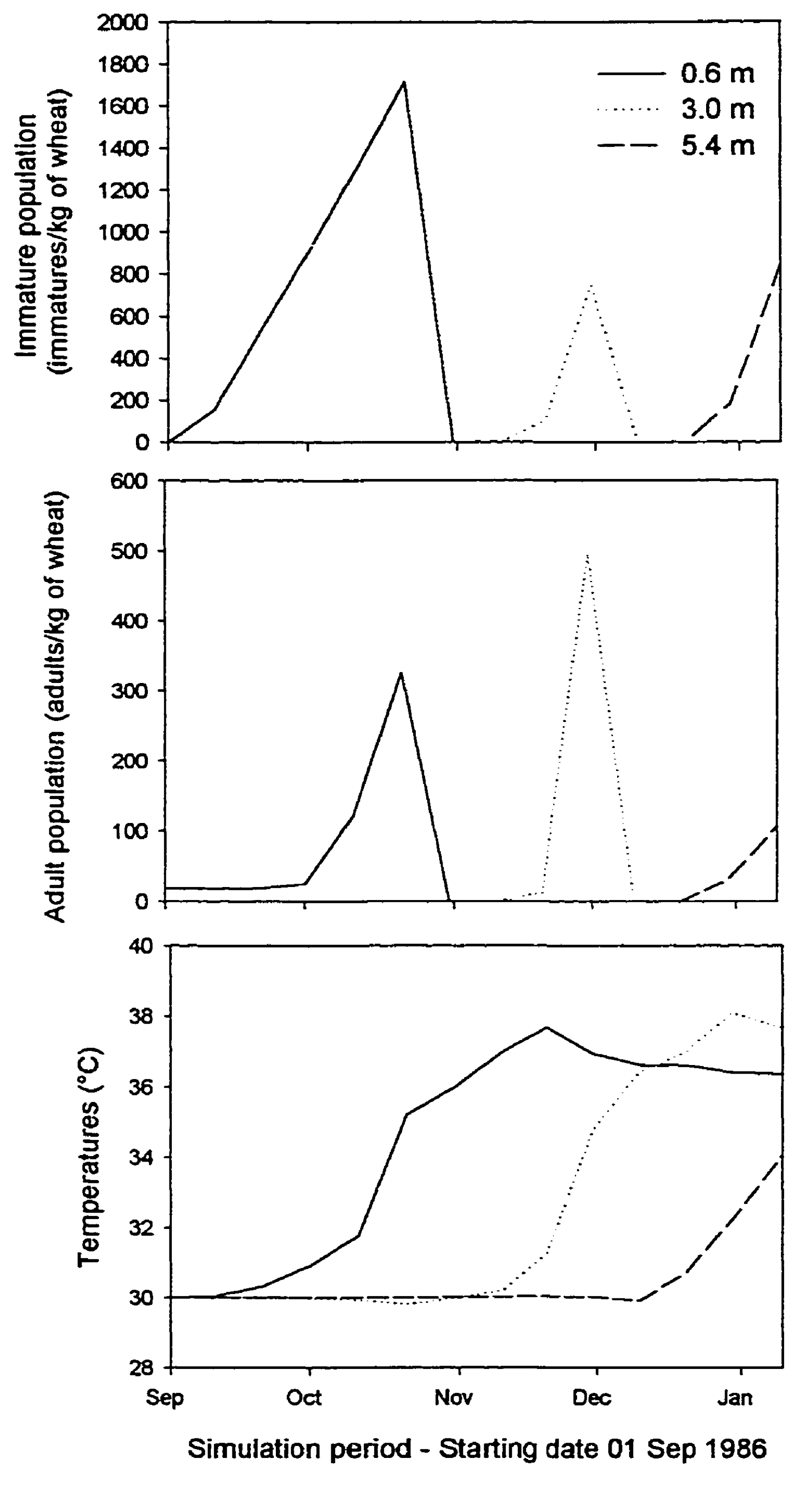


Fig. 17. Predicted temperatures and *C. ferrugineus* population (adults/kg of wheat in a 350-kg grain pocket) at the centre of the grain bulk at three depths in a 6-m diameter bin filled with wheat to a depth of 6-m and 6,000 adult *C. ferrugineus* were introduced at the top-centre of the grain bulk (the bin was perfectly insulated)

development of insects and immature population increased.

In the centre layer, the adult population increased to the maximum of 500 adults/kg and hence produced more heat which in turn increased the grain temperatures. The immature population decreases due to the high temperatures of the hot spot (Fig. 17). Due to the migration of insects, different layers reached the peak centre temperatures at different storage times. In the insulated bin, first occurrence of the hot spot was detected at the top-centre of the grain bulk after 6 wk of storage (Fig. 17). In farm bins, first occurrence of the hot spot was detected at the centre of the grain bulk after 8 wk of storage (Fig. 12).

6. 9 Comparison of predicted and observed temperatures and insect population

Temperatures measured at the radius of 0.05-m and at 0.5-m depth were averaged and compared with the temperatures predicted by the hot spot model at the centre of a 1-m diameter and 1-m tall wheat bulk (Fig. 18). The average absolute differences between predicted and observed temperatures were 3°C in bin I and 4.3°C in bin II. The standard error of estimates* when comparing predicted and observed temperatures were 3.2°C in bin I and 4.6°C in bin II.

The maximum population densities were 150 adults/kg in bin I and 70 adults/kg in bin II (Fig. 19). The hot spot model predicted a peak density of 100 adults/kg at the end of the simulated period (Fig. 19). The maximum temperatures were 27°C in bin I and 24.5°C in bin II. The simulated grain temperature was 21°C throughout the storage period. The

---

* Standard error, $SD = \sqrt{(P_t - M_t)^2 / n}$

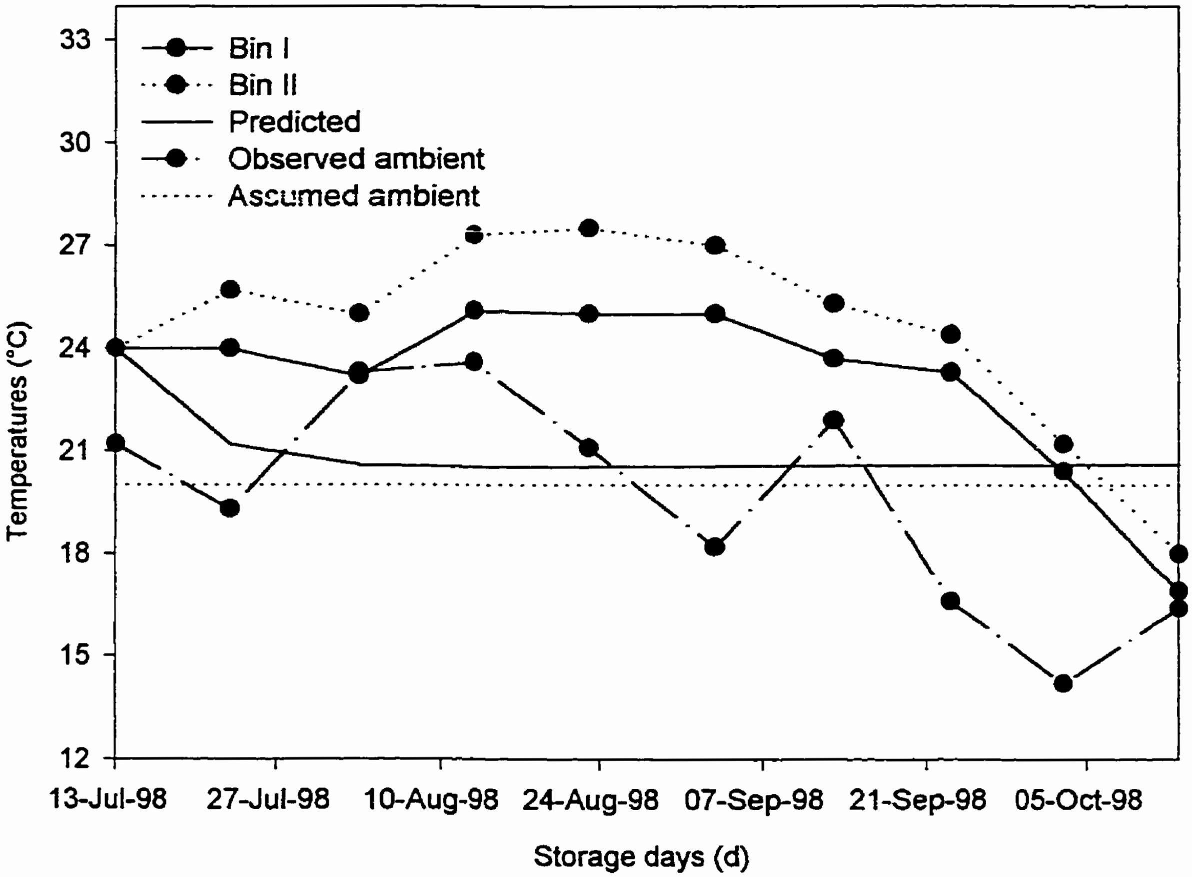


Fig. 18. Predicted and observed temperatures at the centre of a 1-m diameter bin filled with wheat to a depth of 1-m (the bins were in a laboratory)

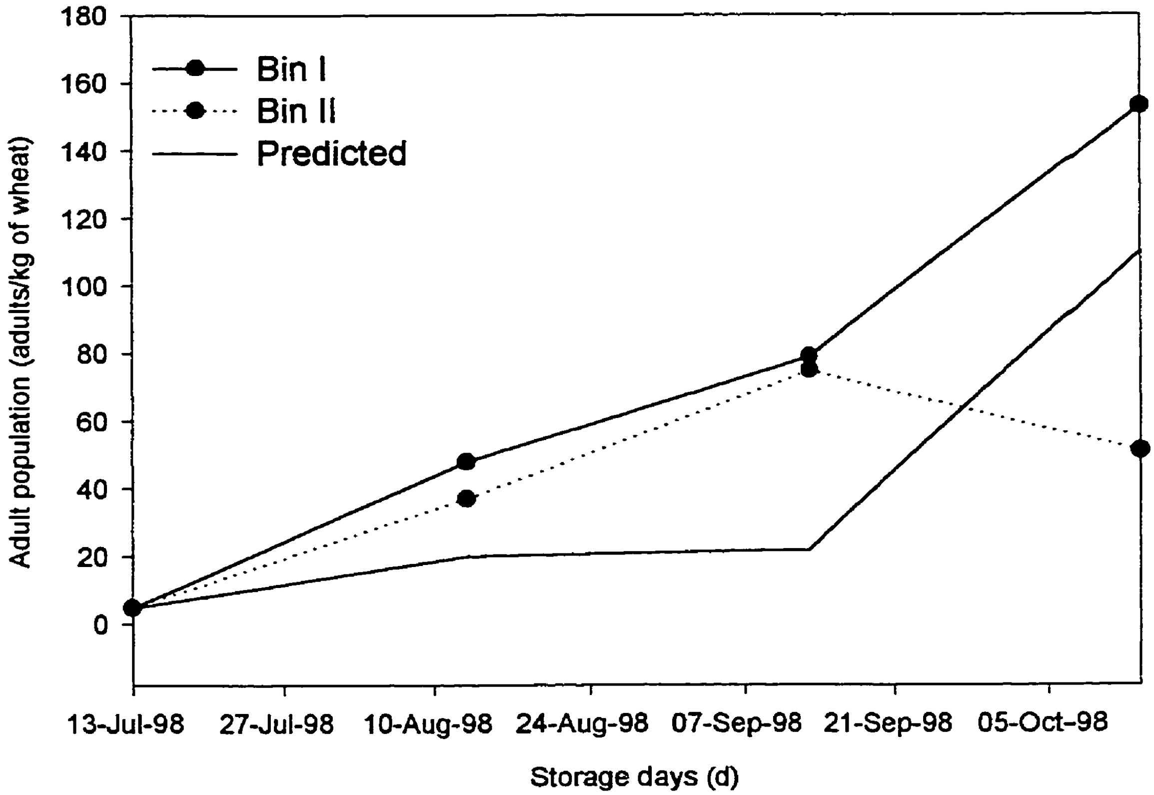


Fig. 19. Predicted and observed population of adult *C. ferrugineus* (adults/kg of wheat) at the centre of a 1-m diameter bin filled with wheat to a depth of 1-m (the bins were in a laboratory)

development and multiplication of *C. ferrugineus* at 21°C are slow. Hence, towards the end of the storage period, the adult population increased to100 adults/kg. Due to the movement of insects from the surrounding grain pockets to the centre of the bulk, the adult population at the centre increased during this initial period of storage.

No hot spot developed in this experiment (Fig. 18). For the given simulation conditions, the hot spot model predicted that the possibility for hot spot occurrence was negligible (Fig. 18) in the 1-m diameter bin, which agreed with the possibility of hot spot occurrence observed in the experiment (The possibility for hot spot occurrence was determined on the basis of simulated temperatures). Because no hot spot developed in the experiment, the development and decline of a hot spot and the effect of a hot spot on its surrounding grain mass were not studied.

The possible reasons for the failure of development of a hot spot in the experiment were:

(1) For the development of a hot spot, a grain pocket must be deep enough to have thermal insulation and a critical population density must be present so that sufficient heat is produced to offset the low ambient conditions. The grain bulk used in the experiment was too small and hence the temperatures of the grain followed the ambient temperatures despite the insulation materials on the grain bin. In this experiment 10,000 adult *C. ferrugineus* were introduced at the centre and on 16th day of storage 5,000 adults were randomly spread at the top surface of the bulk. But for the storage condition used in this experiment, the insect population used was not enough to offset the low ambient temperatures.

(2) Even though wheat was stored at an initial temperature of 28 °C, the grain temperature

dropped to 24°C after 4 wk of storage due to the low ambient temperatures, which varied from 14 to 23°C. The grain temperatures were not favourable for the multiplication of the insects.

(3) The wheat used was at initial moisture content of 13.2% at which it is difficult for insects to puncture the grain.

(4) The wheat used in this experiment was sound wheat (wheat without broken kernels). Insects can not easily puncture the wheat and due to the unavailability of food, mortality of the insects was high. Based on the first sampling only 75% of the initial insect population was alive in the bin.

6. 10 Comparison of the hot spot and spatial models

At an initial insect population of 20 adults and an initial grain temperature of 25°C, no hot spot was predicted by the hot spot model. The temperatures predicted by the hot spot model simulated with insects and without insects were the same (Fig. 20). Even though the insect population increased over the time period, the heat produced by the insects was not sufficient to increase the grain temperatures. Hence the grain temperatures did not increase during the storage period. The maximum difference between the centre temperature predicted by the spatial model and the hot spot model was 5°C at the end of the simulation period. The two-dimensional model of heat transfer, which is a submodel of the spatial model, calculated radiation values on the southern 55% of the bin wall. Because the spatial model does not include the variational heating of the bin wall and predicts the temperatures on only the south side of the bin, the temperatures predicted by the spatial model were higher than those

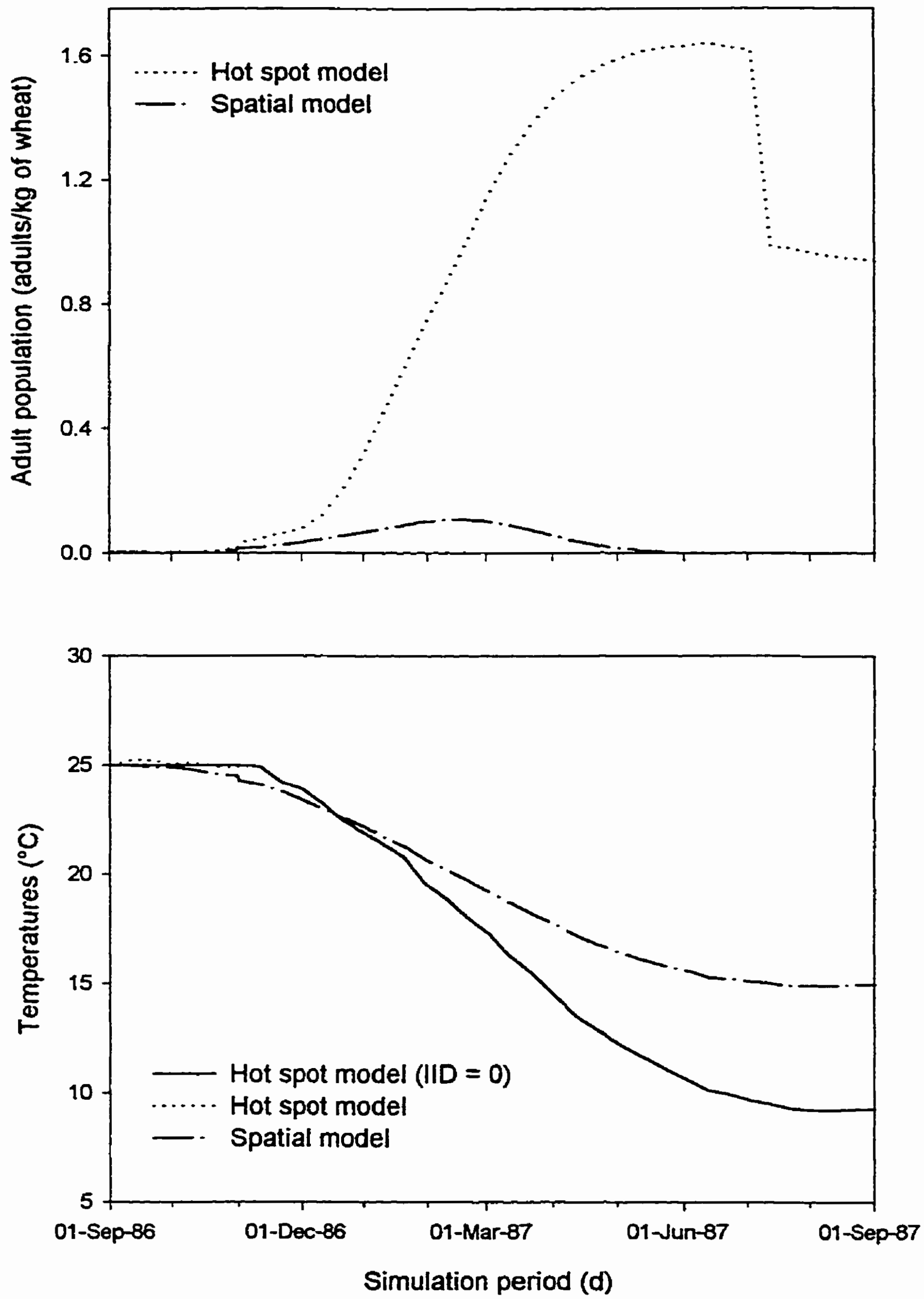


Fig. 20. Average temperatures (°C) and adult *C. ferrugineus* population (adults/kg of wheat) predicted by the hot spot and spatial models at the centre of a 8.5-m diameter bin filled with wheat to a depth of 6-m at Winnipeg, Canada when 20 adults were introduced at the centre of the wheat bulk on 01 Sep 1986 (initial grain temperature = 25°C, total mass of wheat at the centre of the bulk = 5,000 kg)

predicted by the hot spot model.

The insect population densities predicted by the spatial model were increased till the end of the winter and decreased to zero at the end of the following summer. The long development period at low temperatures was the main reason for the slow increase in population. Because grain temperatures fell below 20°C, reproduction and development of the insects were reduced to nearly zero. The model of population dynamics of *C. ferrugineus*, which is a submodel of the hot spot model, predicted continued low development and reproduction at low temperatures. Hence the insect densities predicted by the hot spot model (1.6 adults/kg) were higher than those predicted by the spatial model (0.1 adults/kg) even though the temperatures predicted were lower (Fig. 20). In summer, the temperatures of the grain surrounding the centre of the bulk increased and hence the adults migrated to the surrounding grain pockets from the centre of the bulk. Hence, the adult population at the centre of the bulk decreased in summer (Fig. 20).

For an initial insect density of 10,000 adults and an initial grain temperature of 30°C, the hot spot model predicted hot spots towards the end of the fall (Fig. 21). A peak temperature of 39°C was predicted at the centre of the bulk. Insect population reached a maximum of 120 adults/kg in the hot spot. Because the model then simulates insect migration from the hot spot to the surrounding bulk due to the higher temperature of the hot spot, the insect population decreased and reached nearly zero at the centre of the bulk.

The temperatures predicted by the spatial model were 16°C below the maximum predicted by the hot spot model (Fig. 21). But the population density predicted by the spatial model reached a maximum of 500 adults/kg. In the prediction by the spatial model, the

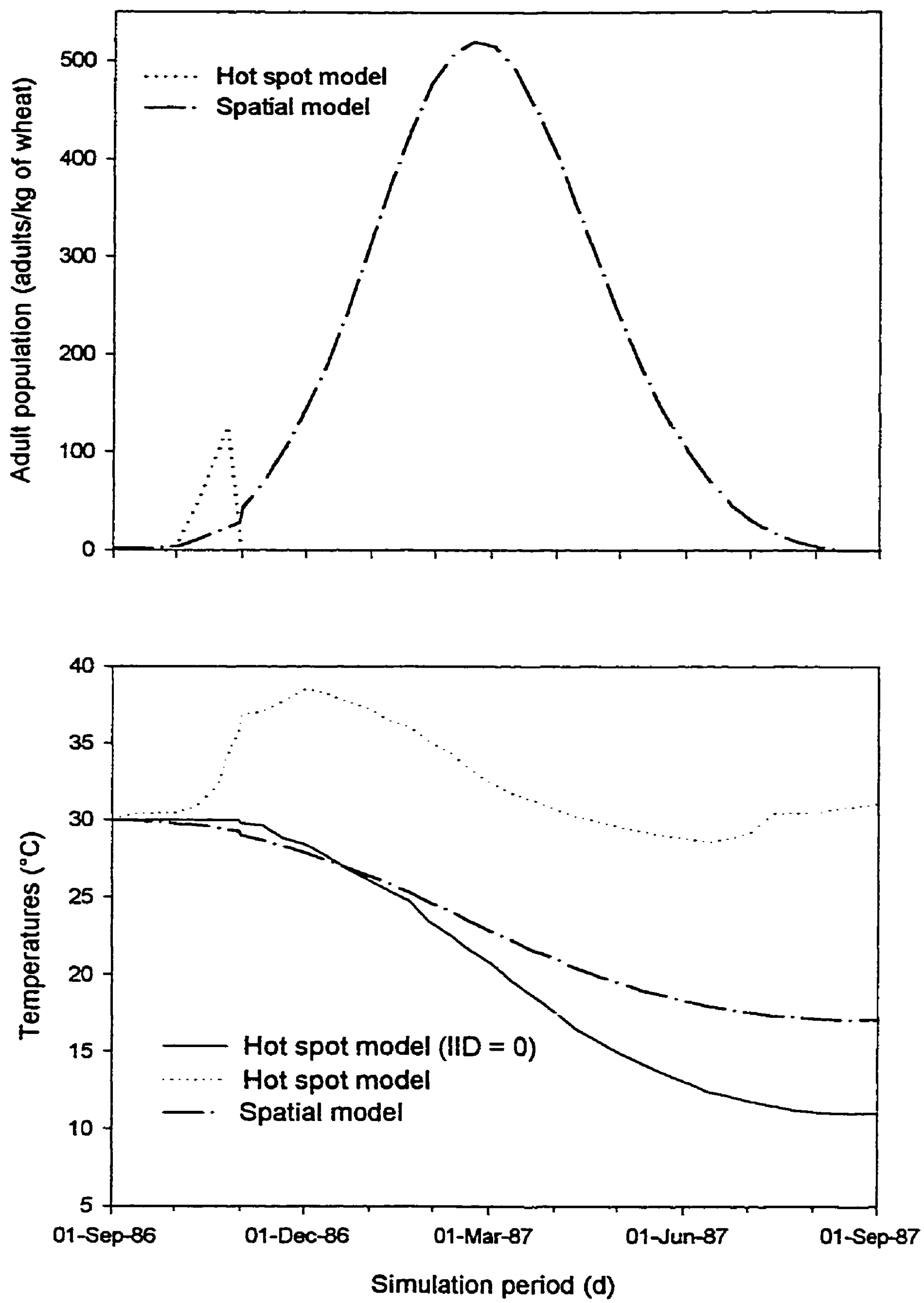


Fig. 21. Average temperatures (°C) and adult *C. ferrugineus* population (adults/kg of wheat) predicted by the hot spot and spatial models at the centre of a 8.5-m diameter bin filled with wheat to a depth of 6-m at Winnipeg, Canada when 10,000 adults were introduced at the centre of the wheat bulk on 01 Sep 1986 (initial grain temperature = 30°C, total mass of wheat at the centre of the wheat bulk = 5,000 kg)

population decreased when the temperature reduced below 20°C. Also the absence of feedback between the heat transfer model and insect model and movement of insects in the spatial model were the main reasons for the prediction of high insect population.

Figure 22 shows the comparison between the spatial model and the hot spot model, when movement of insects was not simulated in the hot spot model. The temperature predicted by the hot spot model at the centre of the bulk reached a maximum of 44°C when the insect population was at the peak of 420 adults/kg. Due to the effects of high temperature and insect density on mortality rate, the insect population at the centre then dropped to 100 adults/kg. Hence the temperature at the centre were also lowered which implied the importance of internal heat generation in determining the grain temperatures. Because the movement of insects was not included in this simulation, the decline of hot spots was not predicted in this simulation. The insect population predicted by the spatial model and the hot spot model reached nearly the same peak insect population (Fig. 22).

The submodels of population dynamics in the hot spot and spatial models were compared by simulating the effects of constant grain temperatures on insect population densities (Fig. 23). At 30°C, the insect population predicted by the spatial model increased as the storage time increased and at the end of simulation reached a peak of 11,000 adults/kg. The hot spot model predicted an earlier development of the insect population when the grain temperature was at 30°C. The insect population reached the peak of 3,800 adults/kg and due to the simulated mortality at the high insect density, the insect population then decreased.

At 25°C the hot spot model predicted a higher insect population (4,000 adults/kg) than that predicted by the spatial model. At 20°C, the hot spot model predicted higher insect

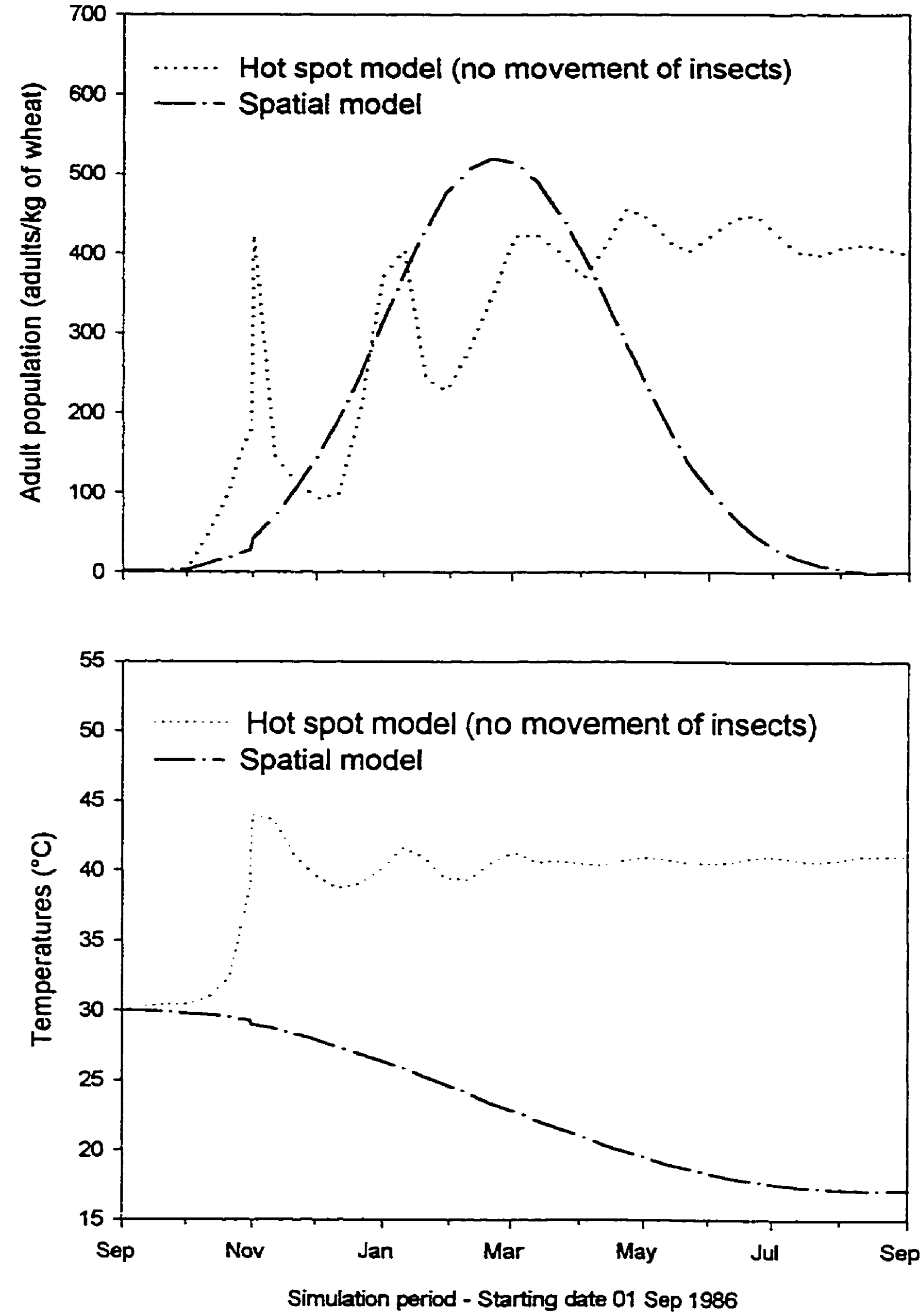


Fig. 22. Average temperatures (°C) and adult *C. ferrugineus* population (adults/kg of wheat) predicted by the hot spot (no movement of insects) and spatial models at the centre of a 8.5 m diameter bin (refer to Fig. 21. for simulation conditions)

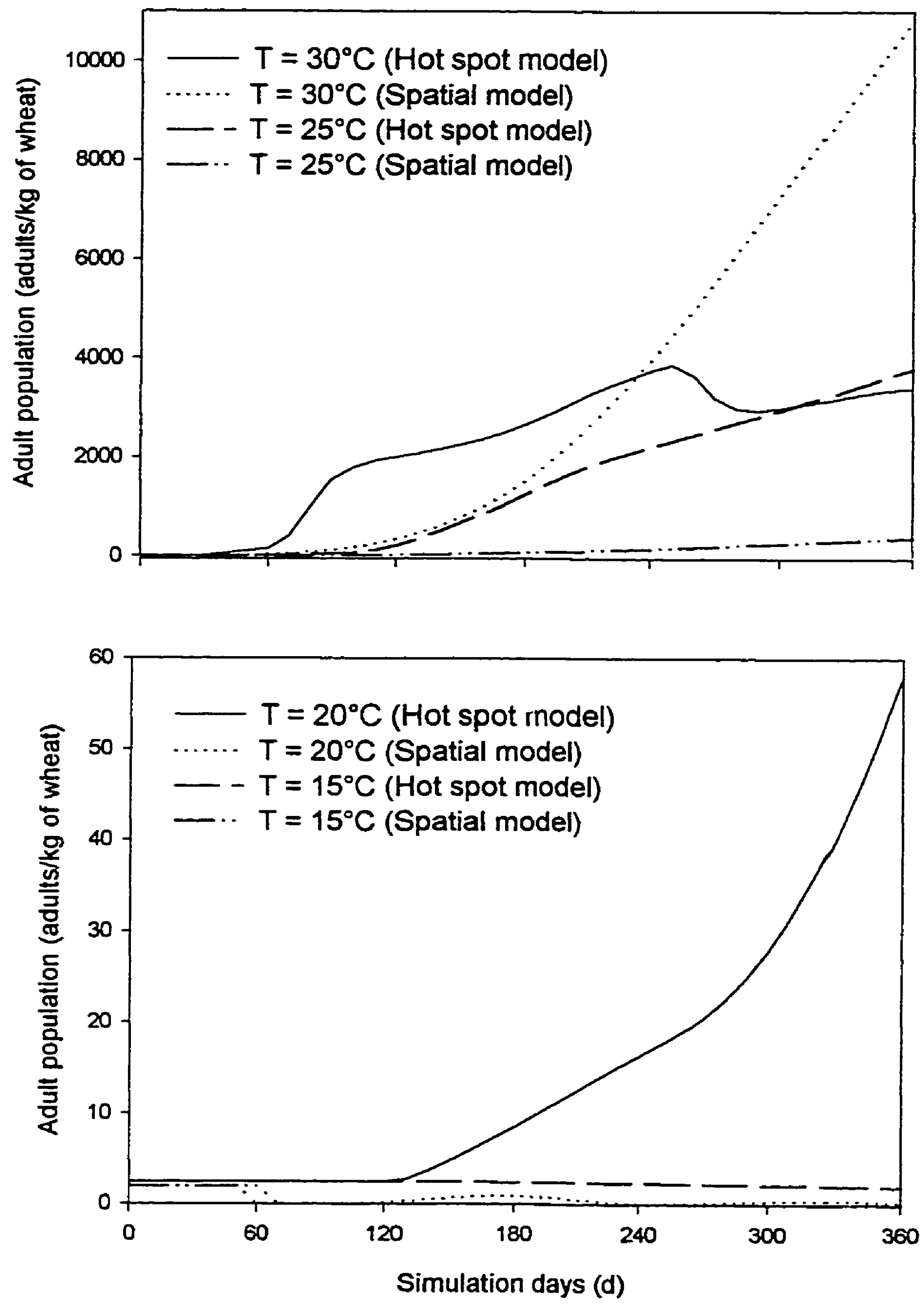


Fig. 23. Predicted adult *C. ferrugineus* population (adults/kg of wheat) at constant temperatures by the hot spot model and the spatial model (initial insect density = 1 newly emerged female/kg of wheat)

population (55 adults/kg) than that predicted by the spatial model. This is because the hot spot model predicted continued low development and reproduction of *C. ferrugineus* at low temperatures. After 62 d of storage, the adult population became zero in the spatial model which is due to the assumption of temperature-independent age distribution. At 15°C, the insect population predicted by the spatial model was zero whereas there was no increase in adult population predicted by the hot spot model.

In summary, the population densities predicted by the hot spot and the spatial models were quite different and the adult population predicted by the hot spot model was lower than that predicted by the spatial model at 30°C and seemed high at low temperatures. The spatial model predicted high adult populations for the temperature of 30°C and for low temperatures the spatial model predicted lower insect population than that predicted by the hot spot model. This variation might be due to the differences between the submodels of population dynamics in the hot spot and spatial models (Refer to section 5.4 of this thesis).

7. CONCLUSIONS

Hot spots induced by *C. ferrugineus* in grain storage bins that are located at Winnipeg, Canada were simulated by using the hot spot model. Starting date of simulation 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 project:

(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 to a depth of 6-m, an initial insect density of 600 adults (1 newly emerged female/kg of wheat) initially introduced at the top-centre of the bulk did not develop hot spots but an initial insect density of 1,300 adults (2 newly emerged females/kg of wheat) developed hot spots at the centre of the grain bulk. The higher the initial insect population, the higher is the possibility and the earlier is the occurrence of hot spots. The higher the initial grain temperature, the higher is the possibility for hot spot occurrences. In grain bulks with an initial grain temperature of 25°C, 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 large diameter bins infested with 10 newly emerged females/kg of wheat, initially introduced at the top-centre of the bulk, hot spots developed earlier and centre temperatures remained warm throughout the storage period. Insects introduced at the top-centre developed hot spots at the centre of the bulk. The centre temperature of the bulk in which insects were introduced at the top-centre of the bulk was

higher than the centre temperature of the bulk in which insects were introduced at the bottom-centre. Insects introduced along the north side of the grain bulk migra ted to the centre of the bulk earlier than when they were introduced along the south side. In both cases hot spots were predicted at the centre of the bulk.

(3) The centre of the bulk is 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 hot spot (a 350-kg grain pocket) developed at the centre of the bulk. Due to the high temperatures of the hot spot *C. ferrugineus* migrated to the surrounding grain bulk and developed hot spots in those regions.

(5) The average absolute difference between the predicted and the observed temperatures was 3°C and the standard error of estimate was 3.2°C. The maximum population density observed in the experiment was 150 adults/kg of wheat and that predicted by the hot spot model was 100 adults/kg of wheat. The possibility for hot spot occurrences predicted by the hot spot model agreed with that observed in the experiment. Because no hot spot was developed in the experiment, the development and decline of a hot spot was not studied.

(6) The temperatures and insect populations predicted by my model and those predicted by the spatial model were quite different. With an initial grain temperature of 30°C and an initial insect density of 10,000 adults, hot spots were predicted at the centre of a 8.5-m diameter grain bulk by the hot spot model. The insect population predicted by the hot spot model reached a maximum of 120 adults/kg and the temperatures at the centre of the bulk reached

a peak of 39°C while the spatial model predicted an adult population of 500 adults/kg and predicted no increase in the temperatures. This is because the spatial model does not include feedback from the insect model to the temperature model.

8. RECOMMENDATIONS FOR FUTURE WORK

8.1 Computer modelling

8.1.1 Extension of the hot spot model: The hot spot model can be made more comprehensive to simulate stored-grain ecosystems by incorporating the following submodels into the hot spot model: (1) moisture transfer, (2) gas transfer, (3) population dynamics, heat production, and movement of other insect species (for example *Oryzaephilus surinamensis*), (4) population dynamics of fungi, (5) respiration of stored grain, fungi, and mites (6) food availability for insects, (7) aeration, (8) insecticide application, and (9) fumigation.

8.1.2 Implementation of the hot spot model: To make the hot spot model available to farmers, the model could be implemented on the World Wide Web. Implementation of the hot spot model in the World Wide Web would be possible by using the computer programming language JAVA. Because the hot spot model was developed in C++ and the computer programming language JAVA supports many features of C++, implementing the model using JAVA should not be difficult. JAVA's concept of Applets can be used for the implementation of the hot spot model.

8.2 Experimental work

(1) An experiment which results in a *C. ferrugineus*-induced hot spot has to be conducted to check the reliability of the hot spot model. Also, the decline of hot spots has to be studied so that the assumptions on hot spot decline can be checked.

(2) Heat production by insects based on their age and the mechanical condition of wheat has

to be studied and included in the model.

(3) The continuous immigration of *C. ferrugineus* into the grain bin through the top and bottom surfaces should be studied under Canadian storage conditions and that has to be included in the hot spot model. The current version of the hot spot model simulates insect populations based on the introduction of adult insects at a specific time of simulation and does not include the immigration of insects.

(4) A detailed study on the effects of grain temperatures and population densities on movement of insects has to be conducted and the current version of the movement submodel can then be revised.

(5) The possibility of using the hot spot model to design an optimum sampling program should be investigated.

9. REFERENCES

Alagusundaram, K. 1989. Three-dimensional, finite element, heat transfer model of temperature distributions in grain storage bins. Unpublished M. Sc. Thesis. Department of Agricultural (now Biosystems) Engineering, University of Manitoba, Winnipeg, MB.

Alagusundaram, K., D. S. Jayas, N. D. G. White and W. E. Muir. 1990a. Finite difference model of three dimensional heat transfer in grain bins. *Canadian Agricultural Engineering* 32:315-321.

Alagusundaram, K., D. S. Jayas, N. D. G. White and W. E. Muir. 1990b. Three dimensional, finite element, heat transfer model of temperature distribution in grain storage bins. *Transactions of the ASAE* 33:577-584.

ASAE. 1997. *ASAE Standards 1997*. St. Joseph, MI: American Society of Agricultural Engineers.

Back, E. A. and R. T. Cotton. 1924. Effect of fumigation upon heating of grain caused by insects. *Journal of Agricultural Research* 28:1103-1116.

Bala, B. K., N. N. Sarker, M. A. Basunia and M. M. Alam. 1989. Simulation of temperature changes during storage of wheat and rough rice. *Journal of Stored Products Research* 26:1-6.

Berry, I. L. 1987. Computer development of insect population models. ASAE Paper No. 87-1084. St. Joseph, MI: ASAE.

Campbell, A. and R. N. Sinha. 1978. Bioenergetics of granivorous beetles, *Cryptolestes ferrugineus* and *Rhyzopertha dominica* (Coleoptera: Cucujidae and Bostrichidae). *Canadian Journal of Zoology* 56:624-633.

Campbell, A. and R. N. Sinha. 1990. Analysis and simulation modelling of population dynamics and bioenergetics of *Cryptolestes ferrugineus* (Coleoptera: Cucujidae) in stored wheat. *Researches on Population Ecology* 32:235-254.

CGC. 1996. *Canadian Grains Industry Statistical Handbook 1996*. Winnipeg, MB: Canada Grains Council. 257 p.

Cofie-Agblor, R., W. E. Muir, Q. Zhang and R. N. Sinha. 1996a. Heat of respiration of *Cryptolestes ferrugineus* (Stephens) adults and larvae in stored wheat. *Canadian Agricultural Engineering* 38:37-44.

Cofie-Agblor, R., W. E. Muir and R. N. Sinha. 1996b. Comparative heat of respiration of five grain beetles in stored wheat. *Postharvest Biology and Technology* 5:167-175.

Cofie-Agblor, R., W. E. Muir, R. N. Sinha and P. G. Fields. 1996c. Heat production by adult *Cryptolestes ferrugineus* (Stephens) of different ages and densities. *Postharvest Biology and Technology* 7:371-380.

Converse, H. H., A. H. Graves and D. S. Chung. 1969. Transient heat transfer within wheat stored in a cylindrical bin. ASAE Paper No. 69-855. St. Joseph, MI: ASAE.

Cuperus, G. W., C. K. Pickett, P. D. Bloome and J. T. Pitts. 1986. Insect populations in aerated and unaerated stored wheat in Okhaloma. *Journal of Kansas Entomology Society* 59:620-627.

Duffie, J. A. and W. A. Beckman. 1974. *Solar Energy Thermal Process.* New York, NY: John Wiley and Sons.

Epperly, D. R., R. T. Noyes, C. W. Cuperus and B. L. Clary. 1987. Control of stored grain insects by grain temperature management. ASAE Paper No. 87-6035. St. Joseph, MI: ASAE.

Farrell J. M. 1998. *Object-oriented programming using C++.* Cambridge, MA: Course Technology.

Fields, P. G. and N. D. G. White. 1997. Survival and multiplication of stored-product beetles at simulated and actual winter temperatures. *Canadian Entomologist.* 129: 887-898.

Flinn, P. W. and D. W. Hagstrum. 1990. Simulations comparing the effectiveness of various stored-grain management practices used to control *Rhyzopertha dominica* (Coleoptera: Bostrichidae). *Environmental Entomology* 19:725-729.

Flinn, P. W., D. W. Hagstrum, W. E. Muir and K. Sudayappa. 1992. Spatial model for simulating changes in temperature and insect population dynamics in stored grain. *Environmental Entomology* 21:1351-1356.

Flinn, P. W., D. W. Hagstrum and W. E. Muir. 1997. Effects of time of aeration, bin size, and latitude on insect populations in stored wheat: a simulation study. *Journal of Economic Entomology* 90:646-651.

Flinn, P. W. and D. W. Hagstrum. 1998. Distribution of *Cryptolestes ferrugineus* (Coleoptera: Cucujidae) in response to temperature gradients in stored wheat. *Journal of Stored Products Research* 34:107-112.

Hagstrum, D. W. and G. A. Milliken. 1988. Quantitative analysis of temperature, moisture, and diet factors affecting insect development. *Annals of Entomological Society of America* 81:539-546.

Hagstrum, D. W. and P. W. Flinn. 1990. Simulations comparing insect species differences in response to wheat storage conditions and management practices. *Journal of Economic Entomology* 83:2469-2475.

Howe, R. W. 1962. A study of the heating of stored grain caused by insects. *Annals of Applied Biology* 50:137-158.

Howe, R. S. 1965. The summary of estimates of optimal and minimal conditions for population increase of some stored product insects. *Journal of Stored Products Research* 1:177-184.

Incropera, F. P. and D. P. Dewitt. 1996. *Fundamentals of heat and mass transfer*. 4th ed. New York, NY: John Wiley & Sons.

Jayas, D. S. 1995. Mathematical modelling of heat, moisture, and gas transfer in stored – grain ecosystems. In *Stored - Grain Ecosystems,* eds. D.S. Jayas, N. D. G. White, and W. E. Muir, 527-567. New York, NY: Marcel Decker, Inc.

Jayas, D. S., Muir, W. E. and N. D. G. White. 1988. Modelling the diffusion of carbon dioxide in stored grain. ASAE Paper No. 88-6013. St. Joseph, MI: ASAE.

Jayas, D. S., K. Alagusundaram, G. Shunmugam, W. E. Muir and N. D. G. White. 1994. Simulated temperatures of stored grain bulk. *Canadian Agricultural Engineering* 36: 239-245.

Jorgenson, S. E. 1994. Recent developments in ecological and environmental modeling. In *Fundamentals of Ecological Modelling*, ed. S. E. Jorgenson, 483-532. Amsterdam, The Netherlands: Elsevier Science Pub. Co.

Kawamoto, H., S. M. Woods, R. N. Sinha and W. E. Muir. 1989a. A simulation model of Population dynamics of the rusty grain beetle, *Cryptolestes ferrugineus* in stored wheat. Ecological modelling 48:137-157.

Kawamoto, H., R.N. Sinha and W. E. Muir. 1989b. Effect of temperature on adult survival and potential fecundity of the rusty grain beetle, *Cryptolestes ferrugineus. Applied Entomology and Zoology* 24 (4):418-423.

Kawamoto, H., R. N. Sinha and W. E. Muir. 1989c. Effects of temperature and relative humidity on egg development of *Cryptolestes ferrugineus* compared with *C. pusillus* (Coleoptera: Cucujidae). *Applied Entomology and Zoology* 25(1):35-41.

Kawamoto, H., R. N. Sinha and W. E. Muir. 1990. Ecosystem modelling to provide early warning of pest infestation of stored grain. In *Proceedings of the Fifth International Working Conference on Stored-Product Protection*. 2019-2026. Bordeaux, France.

Kawamoto, H., R. N. Sinha and W. E. Muir. 1992. Computer simulation modelling for stored-grain pest management. *Journal of Production Research* 28:139-145.

Liberty, J. 1998. *Beginning object oriented analysis and design with C++*. Birmingham, UK: Wrox Press Ltd.

Lo, K. M., C. S. Chen, J. J. Clayton and D. Dadrian. 1975. Simulation of temperature and moisture changes in wheat storage due to weather variability. *Journal of Agricultural Engineering Research* 20:47-53.

Loschiavo, S. R. 1983. Distribution of the rusty grain beetle (Coleoptera: Cucujidae) in columns of wheat stored dry or with localized high moisture content. *Journal of Economic Entomology* 76:881-884.

Loschiavo, S. R. 1984. Insects, mites, and molds in farm-stored grain in the prairie provinces. Bulletin 1595. Agriculture Canada Research Station, Winnipeg, Manitoba, Canada.

Loschiavo, S. R. and R. N. Sinha. 1965. Feeding, oviposition, and aggregation by the rusty grain beetle, *Crytolestes ferrugineus* (Coleoptera: Cucujidae) on seed-borne fungi. *Annals of the Entomological Society of America* 59:578-585.

Manbeck, H. B. and M. G. Britton. 1988. Prediction of bin wall declines. *Transactions of the ASAE* 31:1767-1773.

Metzger, J. F. and W. E. Muir. 1983. Computer model of two-dimensional conduction and forced convection in stored grain. *Canadian Agricultural Engineering* 25:119-125.

Muir, W. E. 1970. Temperatures in grain bins. *Canadian Agricultural Engineering* 12:21-24.

Muir, W. E. 1980. Grain drying and storage in Canada. *Journal of Society Agriculture Structures* 10:91-105.

Muir, W. E. 1997. *Grain Preservation Biosystems,* preliminary version 2. Winnipeg, MB: Department of Biosystems Engineering, University of Manitoba.

Muir, W. E., B. M. Fraser and R. N. Sinha. 1980. Simulation model of two dimensional heat transfer in controlled atmosphere grain bins. In *Controlled Atmosphere Storage of Grains,* ed. J. Shejbal, 385-397. Amsterdam, NL: Elsevier Science Publishing Co.

Muir, W. E., D. S. Jayas, M. G. Britton, R. N. Sinha and N. D. G. White. 1987. Interdisciplinary grain storage research at the University of Manitoba. ASAE Paper No: 87 - 6544. St. Joseph, MI: ASAE.

O'Dowd, E. T., S. M. Kennford, A. J. K. Bisbrown and J. Ferrington. 1988. A mathematical model with cost implications for predicting temperatures in seed stores. Bulletin 16, Overseas Development Natural Resources Institute, Chatham, Kent, UK.

Oxley, T. A. 1948. *The scientific principles of grain storage,* Liverpool, UK: The Northern Publishing Co. Ltd.

Rao, S. S. 1982. *The finite element method in engineering.* Oxford, UK: Pergamon Press.

Rilett, R. O. 1949. The biology of *Laemopheleous ferrugineus* (Stephens). *Canadian Journal of Research* 27:112-148.

Rumbaugh, J., M. Blaha, W. Premerlani, F. Eddy and W. Lorenson. 1998. *Object-oriented modelling and design.* Prentice-Hall, NJ: Prentice-Hall Inc.

Ruth, D. W. and R. E. Chant. 1976. The relationship of diffuse radiation to total radiation in Canada. *Solar Energy* 18:153-154.

Sarker, N. N. and O. R. Kunze. 1991. Finite element prediction of grain temperature changes in storage bins. ASAE Paper No: 91-6560. St. Joseph, MI: ASAE.

Segerlind, L. J. 1984. *Applied Finite Element Analysis.* 2nd ed. New York, NY: John Wiley and Sons.

Silvert, W. 1993. Object-oriented ecosystem modelling. *Ecological Modelling* 68:91-118.

Singh, R. K. 1977. Computer simulation of energy recovery through anaerobic digestion of livestock manure. Unpublished M. Sc. thesis, Department of Agricultural (now Biosystems) Engineering, University of Manitoba, Winnipeg, MB.

Sinha, R. N. 1961. Insects and mites associated with hot spots in stored grain. *The Canadian Entomologist* 93:609-621.

Sinha, R. N. 1967. Grain storage and associated problems - a report on elevator surveys. Report 35. Research Station, Canada Department of Agriculture, Winnipeg, MB.

Sinha, R. N. 1970. A survey of infestations of farm-stored grain by fungi, insects and mites, and hot spots in the Prairie Provinces. Report 2. Research Station, Canada Department of Agriculture, Winnipeg, MB.

Sinha, R. N. 1974. Seasonal abundance of insects and mites in small farm granaries. *Environmental Entomology* 3:854-862.

Sinha, R. N. and H. A. H. Wallace. 1965. Ecology of a fungus-induced hot spot in stored grain. *Canadian Journal of Plant Science* 45:48-59.

Sinha, R. N. and H. A. H. Wallace. 1966. Ecology of insect-induced hot spots in stored grain in Western Canada. *Researches on Population Ecology* 8:107-132.

Sinha, R. N. and H. A. H. Wallace. 1977. Storage stability of farm-stored rapeseed and barley. *Canadian Journal of Plant Science* 57:351-365.

Sinicio, R., W. E. Muir and D. S. Jayas. 1997. Sensitivity analysis of a mathematical model to simulate aeration of wheat stored in Brazil. *Postharvest Biology and Technology* 11:107-122.

Smith, L. B. 1959. Population dynamics of *Cryptolestes ferrugineus* (Stephens). Unpublished Ph. D. thesis. Department of Zoology. University of Nottingham, UK.

Smith, L. B. 1962. Observations on the oviposition rate of the rusty grain beetle, *Cryptolestes ferrugineus* (Stephens). *Annals of Entomological Society of America* 55:77-82.

Smith, L. B. 1963. The effect of temperature and relative humidity on the oviposition of the rusty grain beetle, *Cryptolestes ferrugineus* (Stephens). In *Proceedings of North Central Entomological Society of America* 18:74-76.

Smith, L. B. 1966. Effect of crowding on oviposition, development and mortality of *Cryptolestes ferrugineus* (Stephens) (Coleoptera: Cucujidae). *Journal of Stored Products Research* 2:91-104.

Smith, L. B. 1983. The relationship between wet grain, *Cryptolestes ferrugineus* (Coleoptera: Cucujidae) populations, and heating in wheat stored in granaries. *The Canadian Entomologist* 115:1383-1394.

Smith, E. A. and S. Sokhansanj. 1990. Moisture transport caused by natural convection in grain stores. *Journal of Agricultural Engineering Research*. 47:23-34.

Stroustrup, B. 1997. *The C++ programming language*. 3rd ed. Massachusetts, U.S.A.: Addison-Wesley.

Thompson, L. T., L. G. Villa and O. E. Cross. 1971. Simulated and experimental performance of temperature-control systems for chilled high-moisture grain storage. *Transactions of the ASAE* 3:554-559.

Throne, S. 1995. Computer modelling of stored product pests. In *Stored - Grain Ecosystems*. eds. D. S. Jayas, N. D. G. White and W. E. Muir, 731- 756. New York, NY: Marcel Decker, Inc.

Wallace, H. A. H. and R. N. Sinha. 1962. Fungi associated with hot spots in farm stored grain. Canadian Journal of Plant Science 42:130-141.

White, N. D. G. 1993. Annual costs related to stored-product pests in Canada (losses & preventive measures). Winnipeg, MB: Agriculture Canada Research Branch 4 p.

White, N. D. G. 1995. Insects, mites, and insecticides in stored-grain ecosystems. In *Stored Grain Ecosystems*, eds. D. S. Jayas, N. D. G. White and W. E. Muir, 169-195. New York, NY: Marcel Decker Inc.

White, N. D. G. and S. R. Loschiavo. 1986. Effects of insect density, trap depth, and attractants on trapping *Tribolium castaneum* (Coleoptera: Tenebrionidae) and *Cryptolestes ferrugineus* (Coleoptera: Cucujidae) in stored wheat. *Journal of Economic Entomology* 79:1111-1117.

White, N. D. G., D. S. Jayas and R. N. Sinha. 1987. Interaction of carbon dioxide and oxygen levels, and temperature on survival and reproduction of *Cryptolestes ferrugineus* in stored wheat. *Phytoprotection* 69:31-39.

White, N. D. G. and C. J. Demianyk. 1994. Relative annual insect infestation levels of stored grain on the Canadian Prairies. Agriculture and Agri-food Canada, Winnipeg Research Centre, MB.

Woods, S. M., N. D. G. White and R. N. Sinha. 1997. Simulation of generation times of the rusty grain beetle, *Cryptolestes ferrugineus*, in farm-stored grain in the Canadian Prairies, 1952-1990. *Researches on Population Ecology* 39:47-56.

Yaciuk, G., W. E. Muir and R. N. Sinha. 1975. A simulation model of temperatures in stored grain. *Journal of Agricultural Engineering Research* 20:245-258.

Zhang, Q., W. E. Muir, R. N. Sinha and S. Cenkowski. 1992. Heat production in wet wheat under adiabatic conditions. *Canadian Agricultural Engineering* 34:233-238.

DETAILS OF THE FILES INCLUDED IN THIS DISK

This disk contains program files and appendices of thesis titled "Computer modelling of insect-induced hot spots in stored grain" written by Seshadri Mani (June 1999).

File names	Description (file format)	Size (KB)
I. Appendices		
1. Appendix_A	Classes defined in the hot spot model (word perfect)	24
2. Appendix_B	Attributes defined in the hot spot model (word perfect)	58
3. Appendix_C	Input data for the hot spot model (word perfect)	33
4 Appendix_CFig	Figure showing the sample discretization of a bin (postscript)	17
II. Directories		
D1. Appendix_D	Contains the program files	144
D2. Winnipeg_weather	Contains the weather data for Winnipeg	288
D3. Input_files	Contains the input data files for the model	5

Details of the directories

File names Description

D1. Appendix_D

Note: Files having '.h' extension represent the header files and those having '.cc' extension represent the source files. The following files are in ASCII text format. Word Perfect can be used to open these files.

1. grid	Grid generation
2. integration	Numerical integration
3. boundaries	Boundary conditions
4. population	Population dynamics
5. heatproduction	Heat production
6. movement	Movement
7. solution	Equation solving
8. moisture	Moisture transfer
9. gastransfer	Gas transfer
10. aeration	Changes in temperatures due to ventilation
11. others	Other insect species
12. hotspot	1st of the main program of the hot spot model
13. hotspot_1	2nd part of the main program
14. hotspot_2	3rd part of the main program

D2. Winnipeg_weather

1. wpgsolar	Solar radiation data for Winnipeg (1986-87)
2. wpgtemp	Ambient temperatures for Winnipeg (1986-87)
3. wpgwind	Wind velocity data for Winnipeg (1986-87)

D3. Input_files

1. grid_6m.dat	Two-dimensional grid input data
2. properties.dat	Properties of grain, air, concrete, bin wall material

Procedure to run the model in Unix (Sun Solaris) environment:

The hot spot model was developed in C++ in Unix (Sun solaris) environment. The C++ compilers available in Unix enviroment are: g++, CC, and c++.

Step: 1 Create object file ('.o' extension) for each source file (Command: compiler_name -c source_file_name; e.g. g++ -c grid.cc)

Step: 2 Set the simulation conditions (by changing appropriate parameters in the input files) and the names for result files (by specifying in the hotspot.h file)

Step: 3 Compile the 1st part of the main program linking with the object file of each source file (Command: compiler_name main_program object_file1 object_file2 etc.; e.g. g++ hotspot.cc grid.o integration.o boundaries.o population.o heatproduction.o movement.o solution.o gastransfer.o moisture.o aeration.o)