THE USE OF MODELS IN GRAIN STORAGE

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ABSTRACT

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Grain quality is critical in food and feed grains. Quality and quantity losses due to insect infestations are particularly serious in the tropics.

The use of pesticides to prevent insect infestation is no longer economical or acceptable. Other techniques including the control of the storage temperature are now feasible.

A maize weevil population-growth model and a chilled grain-storage model were combined to form a stored-grain system model. The new model is able to provide valuable information for grain store managers in making prudent systems decisions regarding the maintenance of grain quality.

The system model interactively calculates the grain cooling rate, equipment parameters and the insect population change for specified grain and storage conditions. The conditions of the grain which are conducive to insect development are clarified.

The model output is compared with experimental grain temperatures during bin cooldown of 625 metric tonnes (25,000 bu) maize at the Jorgensen Farms in Williamston, Michigan.

The lack of adequate biological information on the maize weevil requires further study to improve the precision of the population growth prediction.

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LIST OF SYMBOLS

a	Constant for particular grain
α	Constant
b	Constant for particular grain
B	Rates of egg laying
β	Constant (as defined in equation 9)
β	Constant
c_a	Specific heat of dry air (kJ/kg^oC)
c_p	Specific heat of dry grain (kJ/kg^oC)
c_v	Specific heat of water vapor (kJ/kg^oC)
C	Scaling factor (as defined in equation 16)
C	Cannibalism (as defined in equation 11)
d	Death rate constant for predators
E	Number of eggs laid through time (t)
ε	Interparticle void ratio (m^3/m^3)
ε	Width of the lower boundary layer (as defined in equation 14), ^oC
EMC	Equilibrium moisture content, (% dry basis)
f	Fecundity (age specific)
G_a	Airflow rate, kg of air per hour
G	Airflow rate (m^3/hr/tonne as defined in equation 3)
H	Humidity ratio (kg/kg)
h	Heat energy (kJ)

h_{fg}	Latent heat of vaporization (kJ/kg)
K	Carrying capacity of the environment
k	Discrete time
k	Drying constant (as defined in equation 30)
L	Grain depth (m)
M	Average grain kernel moisture, dry basis (decimal)
MR	Moisture ration $(M - M_{eq})/(M_{in} - M_{eq})$
m	Dry mass of grain (kg)
m	Instantaneous rate of mortality
m_K	Dry mass of grain (kg as defined in equation 31)
m_L	Dry mass of air (kg)
N	Size of population at time (t)
n	Number of insects which die
η	Fan mechanical efficiency
P	Pressure (Pa)
P	Predator population (as defined in equation 6)
p	Predation rate increase
ΔP	Positive gain in population
Q	Airflow rate $(m^3/s/m^2)$
RH	Relative humidity
r	Intrinsic population growth rate
r_o	Developmental rate
ρ	Density, kg of dry product per m^3
ρ	Constant rate of population increase to optimum temperature (as defined in equation 12)

LIST OF SYMBOLS (CONTINUED)

S	Cross sectional area (m^2)
T	Air temperature (^oC)
t	Time
T_m	Lethal temperature (^oC)
ΔT	Temperature range over which 'thermal breakdown' is dominant
θ	Product temperature (^oC)
V	Velocity (m/s)
W	Humidity ratio of the air
x	Temperature (as defined in equation 15)
x	Bed-depth coordinate (m)
y	Percentage development per day (as defined in equation 15)
y	Bed-depth coordinate (m)

CHAPTER I

INTRODUCTION

Grain is often stored for periods which exceed the time recommended for optimum quality. Carryover stocks of shelled corn were estimated as exceeding 100 million metric tonnes in the U.S. in summer 1987 (Weinzierl and Porter, 1988). Most storage facilities are not designed for long term grain quality preservation. The surpluses must be stored well to avoid physical and economic losses.

The factors which lead to grain quality deterioration are the grain moisture content, the grain micro-climate, insects, moulds, bacteria, and rodents. Effective control of these factors results in good grain quality.

Insect pests are a major problem encountered in grain storage, especially in the tropics (where the author is employed(i.e. Zimbabwe)). Chemical control is still the most effective control method. The extensive use of chemicals in the tropics is costly and hazardous. The Grain Marketing Board (GMB) of Zimbabwe spent over a million dollars (Z$) on chemical grain pest control last year (April 1, 1987 to March 31, 1988) (see appendix A).

Zimbabwe is a 390,700 km^2 landlocked country located between the 15 to 22^o south latitude and the 26 to 34^o east longitude. Most of the land lies above 600m above sea level and therefore experiences sub-tropical climatic conditions. The population of Zimbabwe is estimated at 8 million (1982 census projection).

Zimbabwe has an unreliable rainfall season occurring between November and March. Harvesting of summer crops begins in April and may be delayed to late August. The topography, soils, and climate of Zimbabwe are not favourable for intensive agricultural production but she has excellent prospects for both increased food production and sales of grain on the international market.

Many chemicals that Zimbabwe and many countries use have been severely restricted; besides, some insects species have built up resistance. Resistance problems have led to a search for alternative insect control techniques in Australia (Hunter and Taylor, 1980) and other countries.

Development of new chemicals is expensive and requires time. Few countries have the technical expertise and resources to develop chemicals. The toxicity of the available chemicals is rarely fully understood. Alternative insect control measures need to be developed to control insects since a reduction in food losses is essential in parts of the world where the food shortage is acute.

Some countries experience chronic shortage of grains because the crops are destroyed in storage within a year after harvest. In Zambia, infestations of <u>Sitophilus zeamais</u> (Motshusky) and

Table 1.1 Grain production in Zimbabwe (1987/88).

Grain	Production tonnes (x10E3)	Harvesting time (usual)	Moisture content * % w.b.
Maize	1236.5	April-May	12.5
Soyabeans	63.5	April-May	11.0
Sorghum	203.9	April-May	12.5
Millet	336.7	April-May	12.5
Wheat	125.0	Aug-Sept.	12.5
Groundnuts	210.9	April-May	7.0
Sunflowers	100.1	May	9.5

* Maximum accepted by the Grain Marketing Board for storage. (G.M.B report, The Herald Nov.8, 1988). Storage extends from a few months to years depending on the demand for the grain.

Sitotroga cerealella (Olivier) have occurred in which 92% of kernels of the maize crop contained holes within eight months after harvest (Hindmarsh and Macdonald, 1980).

Several alternative preservation techniques have been developed for maintaining grain quality. Aeration is the best known. Its objectives are: (1) to stabilize the grain moisture content and grain micro-climate; and (2) to reduce the grain temperature to inhibit insect and mould development. Chilled grain storage is an extension of the aeration technique.

Designing an effective chilled grain aeration system requires knowledge of the dynamics of insect growth and grain deterioration. Simulation modelling is a tool to obtain the optimum design. An insect growth/grain aeration simulation model will result in a better design of aeration systems.

CHAPTER II

OBJECTIVES

The objectives of this study are:

1. To assess the available aeration and insect-population growth models.
2. To combine the aeration and insect growth models into a grain storage system model.
3. To assess the effect of micro-climatic modifications on the insect infestation.
4. To collect temperature / moisture content / insect growth information on an experimental chilled-grain storage facility.
5. To compare the experimental and simulated data.

CHAPTER III

LITERATURE REVIEW

3.1 GRAIN QUALITY

Grain quality is a major issue among grain traders and the Federal Grain Inspection Service (FGIS) in the U.S.A. The FGIS is aiming for 'zero insect tolerance' by 1992 (Anon., 1987) under reduced chemical use conditions. Grain traders have limited options to turn this requirement into reality. Insect resistance to chemicals, strict Environment Protection Agency (EPA) regulations, and consumer concern with chemical residues make quality a critical attribute. Also, international grain buyers have become more critical of grain quality (Hurburgh, 1986; Gilbert, 1986; Hawk, 1986).

Inspection of grain, equipment and facilities must be thorough. Temperature, moisture content and insects must be monitored as long as the grain is in storage. The technology to achieve adequate monitoring without excessive labor is available. These procedures limit the potentially heavy economic damage due to grain quality deterioration and quantity losses.

3.2 AERATION

Aeration is the moving of a relatively low volume of ambient air through the grain to stabilize grain temperature and moisture content. The technique was commercialized in the early fifties because bin turning was no longer economical (Foster and Tuite, 1982).

Airflow rates for different grain moisture levels and geographic regions have been recommended for the U.S.A. (Holman, 1960) (see Table 3.1).

Fan selection is based on the airflow rate, type of grain and grain depth (Foster and Tuite, 1982). These factors determine the resistance of the grain to airflow against which the fan must deliver the required airflow.

The airflow must be adequate to move the cooling zone through the grain within a limited time period to avoid spoilage of the grain in the top layers. The depth of the cooling zone depends on the air velocity through the grain and the rate of heat and mass transfer from the grain to the air (Person et al., 1966).

Pressure-drop data for airflow through agricultural products is empirical. Shedd (1953) determined the pressure-drop for different grains. The values read from the graph must be adjusted for grain that is densely packed or has a high broken corn and foreign matter (BCFM). Fines increase the resistance to airflow; the maximum values are reached when there is 30 to 40% fines present [Foster (1970) as quoted by Brooker et al. (1981)].

Table 3.1 Recommended airflow rates for aerating grain in the United States.

Grain Moisture (%)	Storage Type	Airflow Rates per Metric Tonne Northern States (ω/s)/t	Southern States (ω/s)/t
12 - 15	Flat	0.93 - 1.86	1.24 - 1.86
	Upright	0.47 - 0.93	0.62 - 1.86
15 - 25	Flat	9.30 - 13.95	
	Upright	4.65 - 9.30	

18.6 (ω/s)/t = 1 cfm/bu
Adapted from Holman (1960)

Air distribution through the grain mass depends on the type of aeration system. In a horizontal storage, the critical factors are: duct size, size and spacing of the holes in the ducts, and the length and layout of the ducts (Burrell, 1974). The required duct surface area (duct and holes) must be large enough that the velocity of the air through the grain adjacent to the duct does not exceed 0.15 - 0.25 m/s (Holman, 1960).

Bins are usually equipped with full perforated false floors, partially perforated floors or with ducts for aeration. Full perforated false floors do not create non-uniform air velocities in a bin, partially false floors and duct systems do.

Surveys carried out in Illinois showed that the temperature of the grain at the peaked center of some commercial bins reached $50^{o}C$ while at a distance of 12.2 m., the temperature was $4^{o}C$ (Weinzierl and Porter, 1988). Obviously, the aeration was not uniform. Leveling of the surface of the grain and removal of fines improves the air distribution. Grain spreaders disperse fines evenly in the grain [Stephens and Foster (1976) as quoted by Foster and Tuite (1982)], and thus the use of grain spreaders is recommended if cleaning of the grain is not feasible.

A number of computer packages have been developed to assist in the design of aeration systems to avoid operational problems (Watson, 1987; Bridges et al., 1988). A well designed aeration system also requires effective management to ensure grain quality maintenance (Foster and McKenzie, 1979).

Ghaly (1977) found fifteen times more insects in samples of

peanuts taken from unaerated bins than from aerated bins. Aeration of wheat from an initial temperature of 33^{o} C at 2 liters / second per tonne to 11-21^{o}C preserved the grain for eighteen months without any chemical treatment (Ghaly, 1984); there was an average 2% increase in the initial moisture content of 9.5% (w.b) of the wheat.

The moisture content of the grain determines the length of storage. Moisture content levels and storage periods recommended by the USDA (1968) are often exceeded (Weinzeirl and Porter, 1988) The temperature and moisture gradients in the grain create ideal conditions for mold and insect development. Grain insects particularly flourish in grain that has a BCFM content.

3.3 CHILLED GRAIN STORAGE

Chilling of grain has advantages over aeration because the condition of the cooling air is precisely controlled and is less dependent on the ambient air condition. The ambient air is passed over refrigerated coils at a rate adequate to achieve cooling. The cooled air is reheated sufficiently to reduce the relative humidity to a level in equilibrium with the desired moisture content of the grain (Burrell, 1982). This limits further drying or rewetting of the grain.

Experiments using artificially cooled air in grain storage began in the U.S.A. in the early sixties [(Shove, 1966; McCune et al., 1963; Munday, 1965 as quoted by Shove (1968)]. Commercialization was limited because it was not economic to chill grain when inexpensive pesticides were available.

One hundred metric tons of barley in metal bins were cooled in the U.K. using an airflow rate of 0.4 - 0.7 l/s/ton to 5°C in 60 hours; the ambient conditions were 10 - 23°C (Burrell and Loudon, 1967). Heat gain through the bin walls along with metabolic activity increased the temperature of the grain.

Wheat in concrete silos at an initial temperature between 21 and 21.5°C was cooled in Israel with chilled air flowing at 0.7 l/s/ton to 9.9 - 12.7°C in ninety four hours using a Granifrigor 110 KK unit (Navarro et al., 1973). Problems with the relative humidity control were experienced. Further work (Navarro et al., 1973) with soybeans showed that temperature at the center of the bin 3.5 - 4.5 m below the upper surface heated from 25.5°C to 41°C before cooling. Two cooling cycles lowered the temperature to between 25 and 30°C. Rewetting of the grain occurred near the duct. The average moisture content was reduced slightly. The total energy used was at 9 kW/hr/ton. The use of an evaporator to lower the relative humidity of the chilled air eliminated grain rewetting (Donahaye, Navarro and Calderon, 1974). Six hundred and ninety nine tons of wheat were cooled using an airflow rate of 0.5 - 0.6 l/s/ton from 30 - 37°C to 18 - 19°C in 160 hours using a modified Granifrigor 110 KK unit. Live insects detected in the samples were mainly <u>Rhyzopertha dominica</u> (Fauvel) and <u>Tribolium</u> species.

One thousand metric tonnes of wheat in a steel silo at 8.8% moisture content and 34°C were cooled to less than 10°C in seven weeks and held for seven months (Hunter and Taylor, 1980). The airflow was 1.3 l/s/ton. The researchers concluded that insulation of the bins and recirculation of the air made the systems more effective.

Only limited research has been conducted to assess the benefits of chilling grain on quality. Grain stored at low temperature has a lower respiration rate and the growth of microflora is retarded (Shove, 1968). The problem of toxins (e.g. aflatoxin) is reduced. Grain at a higher moisture content is preferred for livestock feed more than drier grain. There is little dust generated when high moisture grain is handled. Mechanical damage is also reduced considerably. Wheat is usually tempered to between 15 and 17% moisture content before milling; chilled wheat can be stored at that moisture content resulting in drying and tempering cost savings. The viability of seed and barley malt is maintained by low temperature storage (Thorpe, 1985). Insect infestation, which is the main focus of this study, is reduced or eliminated if the grain temperatures are kept below 10°C for twenty six weeks (Evans, 1987; Desmarchelier, 1988). Reduced infestation results in less use of chemical pesticides.

The energy required to dry grain is considerably higher than that required to cool grain (Burrell, 1982). Drying accounts for 86.4 to 87.7% of the total energy used in harvesting, storage, use of maize (Komba et al., 1987). In Michigan, drying costs for maize are 60 - 65% of the total energy costs (Bakker-Arkema, 1988).

3.3.1 Storage System Design Guidelines

Design of any system requires a clear understanding of the critical variables and their interaction in the system. The design factors to be considered in chilled grain storage system design are: (1) grain temperature, (2) grain moisture content, (3) maximum permissible cooling time, and (4) heat gain (Sorenson et al., 1967). The following information is needed to design an effective system:

1. Storage capacity
2. Required airflow
3. Fan type
4. Temperature and relative humidity of the ambient air
5. Length of storage
6. Grain properties/ quality, and allowable time before deterioration begins.

The bin dimensions and the bin volume need to be determined. The grain properties such as bulk density, moisture content and temperature, also must be known.The airflow rate and cooling air temperature determine the cooling time. There are two ways to reduce cooling time: (1) by increasing the airflow rate, and (2) by reducing the air temperature. There are practical limits to the changes that can be implemented. Grain resists air passage. The magnitude of the resistance depends on the type of grain, the bulk density, the percentage of fines and broken kernels, and the grain mass to bin diameter ratio (MWPS, 1987). Low airflow rates are recommended for cooling grain. The required airflow is calculated by multiplying the volume of grain to be cooled by the desired airflow per unit volume per time.

Static pressure is the measure of the resistance encountered in pushing air through ducts, false floors and the grain. It is usually measured in kPa. Airflow delivered by a fan decreases as the static pressure increases.

The airflow resistance equation developed by Hukill and Shedd (1959) has been adopted by the American Society of Agricultural Engineers as a standard (D272.1) (ASAE, 1987). The equation is

$$\Delta P/L = aQ^2/\ln(1+bQ) \qquad (1)$$

where ΔP = pressure, Pa

L = grain depth, m

a = constant for particular grain

b = constant for particular grain

Q = airflow rate, $m^3/s/m^2$

The constants a and b used in the airflow equation for selected grains are listed in table 2. The equation is valid for calculating the static pressure through loose, clean, and excludes the resistance of the perforated metal floor or the ducts. To minimize the pressure drop through false floors or ducts, the hole area must be 10% or more of the total surface area (Brooker et al., 1981).

Table 3.2 Values for constants in airflow resistance equation[1] (equation 1).

Grain	Value of a ($Pa/s^2/m^3$)	Value of b ($m^2/s/m^3$)	Range of Q (m^3/m^2s)
Shelled maize	$2.07*10^4$	30.40	0.0056 - 0.152
Shelled maize (low airflow)	$9.77*10^3$	8.55	0.00025 - 0.0203
Soybeans	$1.02*10^4$	16.00	0.0056 - 0.304
Wheat	$2.70*10^4$	8.77	0.0056 - 0.203
Wheat (low airflow)	$8.41*10^3$	2.72	0.00025 - 0.0203

[1]American Society of Agricultural Engineers data: D272.1 (ASAE, 1987)

Once the required airflow and estimated static pressure are known, the power requirement of the fan can be calculated:

$$\text{Fan power (kW)} = \frac{\text{Airflow (m}^3\text{/s) * Static pressure (Pa)}}{1000 * \eta} \qquad (2)$$

where η is the mechanical efficiency of the fan (it is usually estimated as .5).

The temperature and relative humidity of the air determine the effectiveness of the cooling process. The moisture content of the grain also affects the cooling rate. The density and the specific heat-capacity of the air depends on the temperature. These factors and the airflow rate affect the cooling time. The cooling air must not remove or add excessive moisture from or to the grain.

The required time for the cooling front to pass through the grain can be estimated from an energy balance made on the grain bed. The following assumptions are often made:

1. no moisture transfer
2. low airflow rate
3. the grain temperature near the bin inlet very quickly equals the cooling air temperature.

The energy balance equation is:

$$[\, G_a\, c_a\, \rho_a\, (\theta_1 - T_1)]\, t = W_g\, c_g\, (\theta_1 - \theta_2\,) \qquad (3)$$

where t = time (hours)

θ = the grain temperature (^{o}C)

T = the air temperature (^{o}C)

G = airflow rate (m^3/hr/tonne)

ρ_a = air density (kg/m^3).

The temperature of the air determines the density, and specific heat, and hence the time required to cool the grain. The grain should be cooled to 10^{o}C of the ambient air. The airflow cannot be increased indefinitely because the static pressure and fan power will reach excessive levels.

3.4 INSECT POPULATION GROWTH MODELING

The dynamics of insect population is complex. It has benefitted from simulation modeling. A clearer understanding of the biology and ecology of the insect pests has been gained (Hardman, 1976). Predicting the seasonal occurrence of insects using mathematical relationships is essential for properly scheduling control measures.

An insect population changes because of natality, immigration, mortality, and emigration (Kitching, 1983). Insect population models have been presented by Malthus (1798), Pearl (1925), Volterra and Lotka (1925), Leslie (1945), Hardman (1976a) and Ryoo and Cho (1987).

The population models available in the literature are dynamic or deterministic, and vary in their mathematical complexity. Dynamic models are statistically more realistic than deterministic simulation models.

3.4.1 Malthus Model

A basic dynamic, linear and scalar model developed by Malthus [1798 and quoted by Kitching (1982)] is of the form:

$$\frac{dN(t)}{dt} = rN(t) \qquad (4)$$

where N(t) = the size of the population at time t

r = the intrinsic rate of growth.

The Malthusian model assumes conditions without external limiting factors, maximum level of natality and minimum mortality (Hardman 1976b). Determination of the intrinsic rate of growth with acceptable accuracy is difficult when the insects are in the natural environment.

3.4.2 Verhulst-Pearl model

The Verhulst-Pearl equation is also called the logistic model (Spain, 1982):

$$\frac{dN(t)}{dt} = rN \left(1 - \frac{N}{K}\right) \qquad (5)$$

where N = the size of the population at time t

r = the intrinsic rate of growth

K = the capacity of the environment.

The Verhulst-Pearl model reflects inhibited (logistic) growth;

it was first proposed by Verhulst in 1838 and further developed by Pearl in 1920. The first term on the right hand side of equation (5), rN, indicates unlimited growth while the negative second term (a function of N^2) represents a loss in population due to the crowding interaction of the insects. The population density approaches a steady-state condition in which the increase is balanced by the decrease; the decrease rate is dependent on the density.

The Verhulst-Pearl and Malthus models are similar; they require knowledge of the intrinsic growth rate of the insect. The model requires a reliable estimate of the amount of grain which can support an infestation of a particular insect.

3.4.3 Lotka-Volterra Model

Lotka (1922) further developed the Malthus theory that if a population remains under constant conditions, the growth rate (r) will become constant and the population will assume a stable age distribution. Under these conditions, all age groups grow or decline at the same rate as the entire population and their relative proportions remain constant. Such a stable age distribution occurs after several generations (Ricklefs, 1979).

Lotka (1923) and Volterra (1931) [Kitching, 1982 and Spain, 1982] developed the first model which describes the predator-prey interaction in a homogenous insect population. Thus:

$$\frac{dN(t)}{dt} = rN - pNP \qquad (6)$$

and $$\frac{dP(t)}{dt} = \alpha pNP - dP \tag{7}$$

where N = the prey population

P = the predator population

r = the growth rate constant for prey

p = the predation rate increase

α = the assimilation constant expressing the ratio of predators produced to prey killed

d = the death rate constant for predators.

Gause and Witt (1935) use the Lotka-Volterra model in evaluating the competition between two species:

$$\frac{dN_1(t)}{dt} = r_1N_1 - \frac{r_1N_12}{K_1} - \frac{r_1\alpha N_1N_2}{K_1} \tag{8}$$

$$\frac{dN_2(t)}{dt} = r_2N_2 - \frac{r_2N_22}{K_2} - \frac{r_2\beta N_2N_1}{K_2} \tag{9}$$

where N_1 and N_2 = the populations of species 1 and 2

r_1 and r_2 = the growth rate constants for the two species

K_1 and K_2 = the carrying capacities of the environment for the two species when growing alone

α = a constant relating the effect of species 2 on species 1

β = a constant relating the effect of species 1 on species 2.

Equations (8) and (9) state that the increase in population is equal to the unlimited growth rate less the self-crowding and the species-interaction effects.

3.4.4 Leslie Model

Leslie (1945) devised a method to include in a single matrix all the coefficients necessary to describe natality and survival for each age-class. The procedure allows one to update the population of all age classes simultaneously by using a single matrix vector multiplication. The model assumes that there is no generation overlap. It utilizes a discrete time-step. The use of the matrix gives a reasonable approximation of a dynamic model if the time step is kept small.

The Leslie model requires an accurate estimate of the coefficients (A and B) for use in matrix. The model is able to calculate the number of insects at each growth stage. Stored-grain pests are most damaging at specific stages; a model that provides stage information is therefore appropriate.

The Leslie model is a linear, dynamic matrix-model of the form:

$$y(k + 1) = Ay(k) + Bu(k) \qquad (10)$$

$$
\underset{A}{\begin{array}{c}
\begin{array}{cc}
\begin{bmatrix}
* & 0 & 0 & 0 & 0 & 0 & * \\
* & * & 0 & 0 & 0 & 0 & 0 \\
0 & * & * & 0 & 0 & 0 & 0 \\
0 & 0 & * & * & 0 & 0 & 0 \\
0 & 0 & 0 & * & * & 0 & 0 \\
0 & 0 & 0 & 0 & * & * & 0 \\
0 & 0 & 0 & 0 & 0 & * & *
\end{bmatrix} &
\begin{matrix} \mathrm{I} \\ \\ \\ \\ \\ \\ \mathrm{II} \end{matrix}
\end{array} \\
\mathrm{III}
\end{array}}
\quad
\underset{y(k)}{\begin{bmatrix} y_1\ (k) \\ y_2\ (k) \\ y_3\ (k) \\ '' \\ '' \\ y_n \\ \end{bmatrix}}
+
\underset{Bu(k)}{\begin{bmatrix} \text{Net} \\ \text{Immigrant} \\ \text{terms} \\ \\ \\ \\ \\ \end{bmatrix}}
$$

where I = reproduction coefficients

II = survivor coefficients

III = growth coefficients

k = discrete time

$y_1(k)$ to $y_n(k)$ = insect age-classes

A = development matrix

B = immigration matrix

u(k) = immigration vector

* = coefficient

y = population vector.

3.4.5 Interspecies-competition Model

King and Dawson (1971) described the interspecies competition using a differential equation developed by Rich (1956) for *Tribolium Confusum* (J.duVal):

$$\frac{dE(t)}{dt} = NB - NEC \qquad (11)$$

where E = the number of eggs laid through time (t)

N = the population of insects

B = the rates of egg laying

C = the cannibalism.

The interspecies competition includes cannibalism for insects such as cadelle.

Mertz (1972) also discussed the same pest utilising the Verhulst-Pearl equation (equation 5) without providing any new information.

3.4.6 Temperature-dependent Development Equations

Logan et al. (1976) described the relationship between the developmental rate (1/development-time in days) and the temperature (T) for the McDaniel spider mite below the optimum as:

$$r_o(t) = \alpha \ (1 + k \ \exp -(\rho T))^{-1} \qquad (12)$$

where $r_o(t)$ = the developmental rate

ρ = the constant rate of increase to optimum temperature

α and k = constants.

The development rate-temperature relationship above the optimum is:

$$r(T) \simeq R_o\ (\tau) = C_o\ (1 - \exp(-\tau)) \qquad (13)$$

where $\tau = (T_m - T)/\Delta T$

$r(T)$ = the development rate

C_o = a constant

T_m = the lethal temperature

ΔT = the temperature range over which 'thermal breakdown' is dominant.

Wollkind et al. (1978) further developed equation (13) in the lower region above the optimal temperature:

$$r'(T) \simeq R_o\ (\tau') = C'_o\ (1 - \exp(-\tau')) \qquad (14)$$

where $\tau' = T/\varepsilon$

$r'(T)$ = the developmental rate

C'_o = constant

ε = the width of the low boundary layer.

3.4.7 Diet-temperature Inhibited Growth Model

Lamb and Loschiavo (1981) proposed an inhibited growth equation (Davidson, 1944) to simulate the developmental response of Tribolium Confusum (J.duVal) to diet and temperature variation:

$$y = \frac{K}{1 + e^{(a-bx)}} \qquad (15)$$

where y = the percentage development per day

x = temperature

a, b and K = constants for a particular developmental stage or species.

Equation (15) simulates the initial development of Tribolium Confusum (J. duVal) accurately.

The development-temperature curve does not follow the decline in the developmental rate which occurs within a few degrees of the upper lethal temperature. This was first observed by Stimer et al.(1974) who reported that the effect of diet was greatest at the temperature which causes the highest developmental rate.

3.4.8 Hardman Model

Hardman (1978) developed a comprehensive model for the rice weevil development in stored wheat. The Hardman model utilizes several equations to account for the effect of temperature, grain moisture content and population density on the rate of oviposition and the depletion of oviposition sites during population growth. The model was used to analyse the benefits associated with the cooling and drying of grain.

The Hardman model simulates the effect of moisture content on insect development and employs a scaling factor (C_1) which is a linear function of the grain moisture content (W, % w.b.):

$$C_1 = 1 \quad \text{when } W > 13.5 \qquad (16)$$

$$C_1 = 0.84 + 0.0533(W-10.5)$$
$$\text{when } 10.5 < W < 13.5. \qquad (17)$$

The number of insects (n) which die in time t (degree-days) is equal to:

$$n = 1 - e^{-mt} \qquad (18)$$

where m is the instantaneous rate of mortality.

The value of m was determined using data developed by Bailey (1956).

The Hardman model calculates the rice weevil fecundity using the following empirical equation:

$$E = 0.5a\ f\ C_2\ C_3\ t/93.8 \qquad (19)$$

where E = the number of eggs laid by population a with 0.5 of the insects being assumed female

f = the fecundity (age specific)

C_2 = the moisture content factor

C_3 = the population density factor

$t/93.8$ = time in degree-days.

The moisture content and density factors C_1 and C_2 are calculated as follows:

$$C_2 = 0.467 + 0.266\ (W - 12.5) \quad \text{when } 12.5 < W < 14.5 \qquad (20)$$

$$C_2 = 0.252 + 0.215\ (W - 11.5) \quad \text{when } 11.5 < W < 12.5 \tag{21}$$

$$C_3 = 2.99d^{-0.28} \quad \text{when } d >= 50 \tag{22}$$

The density factor is equal to 1.0 when the population is less than 50 adults per 10,000 kernels ($d < 50$).

The Hardman model also calculates the number of laid eggs and their distribution in the grain bulk. The computation of the egg-distribution is not adequately explained. Neither is it indicated why the model is called logistic.

The values of the main factors in the Hardman model are experimentally determined.

Hardman's model has limitations for the modeling of stored-product insect development since it is only valid within the temperature range of increasing insect development. Ryoo and Cho (1987) corrected this disadvantage and developed a model for the rice weevil in rice.

3.4.9 Ryoo-Cho Model

Ryoo and Cho (1987) developed a growth model for the rice weevil by combining the models of Logan et al. (1976) and Wollkind et al.(1978), (equation 12 13 and 14); the Ryoo/Cho model predicts the lower and upper thresholds for the rice weevil in rice to be 15 and 34.1^{o}C, respectively.

Ryoo and Cho also used equations 12, 13 and 14 to develop an equation for development temperatures above and below the optimum:

$$r_u(T) = \alpha\ ((1 + k\ \exp(-\rho T))^{-1} - (1 + k\ \exp(-\rho T_m))^{-1}\ \exp(-\tau)$$
$$-(1 + k)^{-1}\ \exp(-\tau')) \qquad (23)$$

where $r_u(T)$ = the developmental rate

T = temperature above the lower threshold.

Ryoo and Cho recommended the use of iterative methods to calculate the parameters in equation 23.

The Ryoo/Cho paper provides inadequate information on the determination of the constants in the equations and on the effect of moisture content on the constants.

3.4.10 Comparison of Models

Anthropod population development models are generally versions of the models discussed above. Each model has some advantages over the others. The models are generally inadequate for a complex biological system.

The choice between the available models depends on the information desired from the model, the knowledge of the variables that affect insect development, and on the acceptability of the assumptions.

All the models make the assumption that the initial insect population is known. The Malthus and Verhulst-Pearl models assume that the intrinsic growth rate (r) of the insect is also known or can be estimated. Laboratory experiments can be used to determine the intrinsic growth rate but the influence of the critical variables such as grain type and moisture content, insect type and ecology, temperature and relative humidity are rarely fully understood. The interactions of these variables are not the same under different conditions. The calculation of the growth rate is critical to the accuracy of the results from these models.

Relative humidity and temperature (Howe, 1965), food quality (Smith, 1966), and crowding (Mertz, 1972) are the major factors which affect population development of stored-product pests.

The Lotka-Volterra model is an improved Malthus model; it reduces the limitation of the Malthus model since it includes all intrinsic factors that affect development in one variable in (r).

The Leslie model utilizes several coefficients to calculate the population of each growth stage. The difference in the development rates can be built nto the matrix to reduce the inaccuracy caused by combining all stages. Extensive biological information can be included in this model by modifying the coefficients.

The interspecies competition model is also similar to the Malthus model; the difference is that the model directly calculates the number of eggs laid and not the population growth.

The difficulties experienced by entomologists and biologists in developing insect growth models have encouraged mathematicians to develop appropriate equations. However, the critical biological information tends to be inadequately represented in the equations. The application of these models is therefore still of limited practical value.

The diet-temperature inhibited growth model uses only two variables. The usefulness of the model is thus limited.

The Ryoo-Cho model is mathematically based and is not easy to use because of the difficulty in estimating the constants.

The Hardman model uses several equations to reflect the effect of the most of the critical variables. The model is the most comprehensive insect growth model presently available in the literature.

The models reviewed above are mathematically sound but need several supporting equations to account for the physical behaviour of the insects. The models will provide extensive information if insect-specific physical equations can be developed.

There are a number of analytical models which have been developed to simulate the effect of enzymes on chemical reactions; their use to predict insect development has been considered. The models are not discussed here because they do not appear to be applicable to this area of study. Two models which might be useful are the Michaelis-Menten model of enzyme saturation and the Langmuir absorption model (Spain, 1982).

Biological simulation models require the input of mathematicians, entomologists and engineers to ensure that the models provide useful information for predicting the seasonal occurence of insects.

3.5 Maize Weevil Biology

The genus Sitophilus is part of the sub-family Calandrinae, Family Curculionidae. The maize weevil, Sitophilus zeamais is one of the three species in the family.

The female weevil uses strong mandibles to chew a hole in the grain kernel. She deposits a single egg in the hole and seals it with a gelatinous material. The egg-plug provides the only external evidence that a kernel is infested. Each female lays 200-400 eggs during her lifetime of 80- 150 days (Sinha 1985), at a rate of 5 eggs per day. The eggs hatch into larvae in 5 to 10 days and feed entirely within the kernel (hidden infestation). The larvae develop completely within the kernel and are protected from predators as well as sudden fluctuations in temperature, moisture or relative humidity.

There are four larval instars (stages); larvae change slightly from one stage to the other before they become pupae. At the end of the fourth instar, the larvae uses a mixture of frass (which is made up of cast exoskeletons, egg shells and fecal materials) and larval excretion to form a smooth-lined pupal cell. The larval stage lasts 15-40 days. Larvae then assume a pre-pupal stage before they transform into pupae; this stage lasts from 5 to 15 days. The newly-developed adults remain inside the kernel for several days before emerging. Table 3.3 summarizes the life cycle of the maize weevil under two sets of conditions.

The temperature, relative humidity, moisture content of the grain and the oxygen concentration of the air have an effect on the rate of the physiological development and activity of the life stages of the insect. The temperature and relative humidity have the greatest effect on the physiological development.

TABLE 3.3 Mean duration of immature stages (in days).

Stage	Sharifi & Mills (1971) 27°C / 70% R.H.	Howe (1952) 25°C / 70% R.H
Egg	6.5	6.1
Total larvae	18.1	21.6
Pupa	6.3	6.9
Pre-adult	5.3	5.7
Total Immature	36.2	40.3

Adapted from Longstaff (1981)

Female insects do not oviposit when the relative humidity is less than 60% [Chestnut and Douglas (1971) as quoted by Hindmarsh and Macdonald (1980)]. A study by Okelana and Osuji (1984) in Nigeria showed that oviposition occurs when the relative humidity is below 60% but adult the emergence is zero at 30%, 5% at 50% and 18% at 70% relative humidity. The females of many stored-product pests cease to lay eggs at 12 - 15°C (Sinha, 1985). Eggs do not hatch if the temperature is 15°C or less even if they have been laid at a high temperature.

The minimum threshold for the development from egg to emerged adult for the rice weevil is 12.6°C (Hardman, 1978) and 15°C (Ryoo and Cho, 1987).

The adult stage of insects is not as susceptible to unfavourable environmental conditions as the premature stages. If the temperature is too low for physiological development, the insect survives by reducing its locomotive activities. If the temperature exceeds 40°C, insects move away or die.

Sitophilus zeamais is likely to develop if the moisture content of the grain is between 11.5 and 14.5% and the temperature is less than 40°C; 12.5% is the optimal moisture content for feeding and reproduction (Wilbur and Mills, 1985). Moisture above 14.5% may lead to molding if the temperature is favourable and caking and heating may occur. A moisture content of less than 11.5% limits the consumption of grain by the maize weevil. However, if the temperature is over 32°C, weevils can reproduce in the grain at 10% moisture content and even survive at 9%.

The development of the insect from egg to adult is optimum when the temperature is between 21 to 31°C and the relative humidity is about 70% although development may occur at 17 - 34°C and 45 - 100% relative humidity (Sinha, 1985); there is a 25% increase in population every four weeks under optimum conditions. Hardman (1978) presented data on the effect of temperature and moisture content of grain on Sitophilus oryzae (Table 3.4).

Development in multiple infested kernels is slower than in singly infested kernels. The emerging adults are more likely to be smaller, which affects their fecundity. The same variation occurs when a weevil infests grain with small kernels.

3.6 ECONOMIC THRESHOLDS

Insect control measures must be applied at the most economic time which is often considered as the time when the loss caused by the pest just equals the cost of control. To establish such a time, a critical threshold insect density or economic threshold must be determined. An economic threshold is the pest population density at which active control measures must be initiated to prevent the pest from reaching an economic injury level (Pitre et al., 1979)

Table 3.4 Median period to develop from egg to adult for *Sitophilus Oryzae* (in days).

Temperature	Moisture Content of the Grain (% w.b)							
(°C)	10.5		11.5		12.5		13.5	
	**	*	**	*	**	*	**	*
16	-	-	146.0	-	135.0	-	135.0	138.0
20	-	-	45.5	68.8	58.3	67.0	53.0	60.9
24	44.1	46.4	40.8	46.1	39.2	45.5	37.6	39.8
26	34.0	-	30.4	33.6	29.6	31.5	28.0	30.2
32	50.5	-	30.0	45.5	37.0	46.2	30.8	37.5

Adapted from Hardman (1978)

** singly infested kernels
* multiply infested kernels

CHAPTER IV

DESCRIPTION OF THE MODELS

4.1 THE FIXED-BED DRYING/COOLING MODEL

The Michigan State University fixed-bed grain drying model (Bakker-Arkema et al.,1974) has been adapted for grain cooling successfully. The following assumptions were made to develop the drying model:

1. no appreciable volume shrinkage occurs during the drying or cooling process
2. no temperature gradients exist within each grain particle
3. particle to particle conduction is negligible
4. airflow is plug type
5. bin walls are adiabatic with negligible heat capacity
6. $\partial T/\partial t$ and $\partial H/\partial t$ are negligible
7. the heat capacities of moist air and of grain are are constant during short time periods.

4.1.1 Analysis

The cooling of moist grain involves the simultaneous processes of heat and mass transfer. In this research, air moves through the grain and gains or loses heat and moisture.

Energy and mass balances are written on a differential volume

(Sdx) located at an arbitrary position in the fixed bed.

There are four unknowns in this problem (see fig. 1): M, the average grain kernel moisture content; W, the humidity ratio of the air; T, the air temperature; and θ, the kernel temperature. Four balances are made, resulting in four equations.

Enthalpy of the air:

The air gains or loses heat to the control volume Sdx. The amount of air flowing past the plane at x into Sdx in time dt is:

$$(\rho_a V_a + \rho_a V_a W) Sdt \tag{24}$$

The enthalpy of the air flowing into (Sdx) in dt is

$$(\rho_a V_a c_a + \rho_a V_a W c_v) STdt \tag{25}$$

The energy balance for the air passing through (Sdx) in dt is

energy out = energy in - energy transferred by convection

$$\begin{aligned}(\rho_a V_a c_a + \rho_a V_a W c_v)\ \partial T/\partial x\ dxSdt &= \\ (\rho_a V_a c_a + \rho_a V_a W c_v)\ STdt &- \\ (\rho_a V_a c_a + \rho_a V_a W c_v)\ (T + \partial T/\partial x\ dx)\ Sdt &\end{aligned} \tag{26}$$

Enthalpy of the grain:

The energy transferred by convection from the grain to the air is equal to enthalpy lost by the cooling the grain plus energy for evaporating any water from the kernels.

energy transferred = change in internal product energy - energy for evaporation

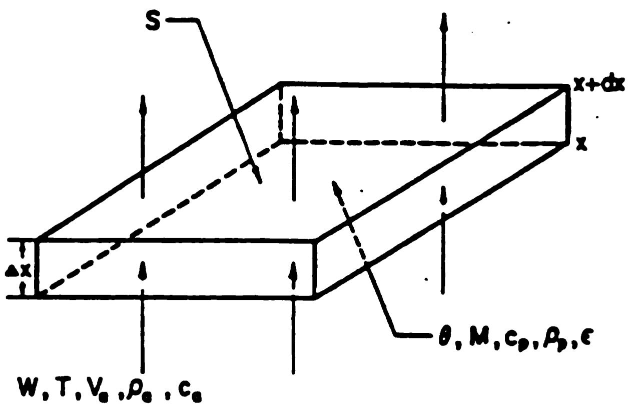

Figure 4.1 Elemental bed volume (Brooker et al., 1981).

W = the humidity ratio of the air
T = the air temperature
θ = the product temperature
V_a = air velocity
ρ_a = air density
M = the average grain kernel moisture content (d.b)
c = specific heat
ε = interparticle void ratio
S = cross-sectional area of bed.

$$h_a \, Sdx \, (T - \theta)dt = (\rho_p \, c_p + \rho_p \, c_w \, M) \, Sdx \, \partial\theta/\partial t \, dt - [h_{fg} + c_v \, (T-\theta)] \, G_a \, \partial H/\partial x \, dx \, Sdt \quad (27)$$

Humidity of the air:

The change in the humidity ratio of the air with respect to x is:

$$G_a \, S(W + \partial W/\partial x \, dx)dt - G_a \, SWdt = G_a \, S \, \partial W/\partial x \, dx \, dt \quad (28)$$

The change in the moisture content of the grain in the control volume in time dt is:

moisture transferred = moisture in - moisture out

which is:

$$\rho_p \, Sdx \, \partial M/\partial t \, dt = G_a \, SH \, dt - G_a \, S \, (H + \partial H/\partial x \, dx) \, dt \quad (29)$$

Moisture content of the grain:

Equations like the Sabbah equation (Brooker et al., 1981) or other suitable empirical thin-layer equations can be used.

The choice is influenced by the temperature range of the product. Thus (Brooker et al.,1981):

$$MR = \exp(-k(t^{.664}) \quad (30)$$

$$\text{where} \quad k = \exp(-xt^{y})$$

$$x = (6.0142 + 1.453 * 10^{-4})(rh)^2)^{0.5} - \theta(3.353 * 10^{-4} + 3.0 * 10^{-8} (rh)^2)^{0.5}$$

and $$y = 0.1245 - 2.197 * 10^{-3} (rh) + 2.3 * 10^{-5} (rh)\theta - 5.8 * 10^{-5} \theta$$

The thin-layer drying equation is suitable for corn in the temperature range between 2.2 and 21.1 °C (Brooker et al., 1981).

Boundary conditions:

1. The inlet temperature and moisture content of the grain must be known at the start of the cooling period.
2. The initial or inlet temperature and absolute humidity of the cooling air must also be known.

$$T(0, t) = T(\text{inlet})$$
$$\Theta(x, 0) = \Theta(\text{initial})$$
$$W(0, t) = W(\text{inlet})$$
$$M(x, 0) = M(\text{inlet})$$

The differential equations (equations 26,27 and 29) along with the thin-layer equation (30) constitute the simulation model for a fixed bed corn dryer or cooler. Since an analytical solution to the system of equation is impossible, numerical techniques are used. In this case, the model is solved by finite difference techniques.

4.2 THE AERATE DRYING/COOLING MODEL

AERATE (Michl, 1983) is a simplified grain drying/cooling model which was developed at the Agricultural Engineering Department of the University of Hohenheim in the Federal Republic of Germany. The original model simulates the following drying/cooling operations:

1. continuous aeration without heating of air;
2. continuous aeration with continuous heating of air;
3. continuous aeration with time-controlled heating of air;
4. continuous aeration with humidity-controlled heating of air;
5. continuous aeration with humidity-regulated heating of air;
6. aeration with aeration time controlled with no heating of air;
7. aeration within a specified humidity range with no heating of air;
8. aeration with fixed inlet conditions/chilling.

The model has been expanded and modified at MSU (Maier,1988). The simulation employed in this study is with fixed conditions with or without heating or cooling of air. The aeration simulation program uses hourly weather data as input air conditions. Weather data for any area or season can be used. Simulation of grain chilling is only possible with fixed inlet air conditions unless a file with "chill" temperatures is provided.

AERATE calculates aeration and chilling behaviour of a grain pile and the energy consumption for a selected procedure.

The simulation calculations are based on mass and energy balances performed on the grain layers within the pile. The input conditions for the bottom layer at the beginning of a time interval are determined by the incoming cooling air. The humidity of the air at the end of the cooling interval for the bottom layer is estimated, and from the following mass balance the grain moisture content at the end of the interval is calculated:

$$M_{K2} = M_{K1} + \frac{m_L{}^* (H_{L1} - H_{L2})}{m_K} \qquad (31)$$

where H_L = absolute humidity of air [kg/kg]

M_K = moisture content of the grain [d.b. kg/kg]

m_K = dry mass of grain [kg]

m_L = dry mass of air [kg]

1 = state of the air or grain at the beginning of a cooling or aeration interval of a layer

2 = state of the air or grain at the end of a cooling or chilling interval of a layer.

The mass balance is based on the assumption that the total sum of the grain and air mass at the beginning of the cooling/chilling interval is equal to the total sum of the grain and air mass at the end of the drying/cooling interval.

Using the estimated air humidity at the end of the interval and the calculated grain moisture at the end of the interval, the temperature of the grain (and the air) at the end of the time interval of the bottom layer is calculated from the following energy balance:

$$\theta_{K2} = T_{L2} = \theta_2 = \frac{h_{K1} + h_{L1} - h_B - h'_{L2}}{h_{K2} + h''_{L2}} \qquad (32)$$

where $h_B = m_L * h_{BW} * (H_{L2} - H_{L1})$

$h_{K1} = m_K * (1 + M_{K1}) * c_{pKF1} * \theta_{K1}$

$h_{K2} = m_K * (1 + M_{K2}) * c_{pKF2}$

$h_{L1} = m_L * c_{pL} * T_{L1} + m_L * H_{L1} * (h_{fg} + c_{pD} * T_{L1})$

$h_{L2} = h'_{L2} + h''_{L2}$

$h'_{L2} = m_L * H_{L2} * h_{fg}$

$h''_{L2} = m_L * c_{pL} + m_L * H_{L2} * c_{pD}$

and

θ_K = grain temperature [^oC]

T_L = air temperature [^oC]

c_{pD} = specific heat of water vapor [kg/kg/^oC]

c_{pKF} = specific heat of wet grain [kJ/kg/^oC]

c_{pL} = specific of dry air [kJ/kg/^oC]

h_{BW} = binding energy of water in grain [kJ/kg]

h_{fg} = latent heat of vaporization [kJ/kg]

h_K = enthalpy of grain [kJ]

h_L = enthalpy of the cooling/chilling air [kJ]

H = humidity of the air

Subscripts 1,2 = layer number.

It is assumed that due to the low air velocity, a temperature equilibrium is established between the grain and the air. Thus, the temperature of the grain in the pile is equal to the air temperature in the pile.

The energy balance is based on the assumption that the cooling/chilling process is adiabatic, i.e. the energy of the air flowing through a layer added to the energy of the grain in the layer remains constant.

Since the outlet air humidity for the bottom layer is an estimate, the calculated air (and grain) temperature and the calculated grain moisture at the outlet of the layer are used in the grain-specific Chung-Pfost equation to determine the equilibrium relative humidity between the grain and the air at the outlet of the bottom layer:

$$RH_{EMC} = \exp(-A * \exp(-B * M_{K2})/1.987 * (T2 + C) \quad (33)$$

where RH_{EMC} = equilibrium relative humidity [decimal]

A,B,C = grain specific constants.

The absolute equilibrium humidity is then calculated from the following equation:

$$H_{EMC} = 0.622 * RH_{EMC} * P_{sat}/(P_{atm} - RH_{EMC} * P_{sat}) \quad (34)$$

where H_{EMC} = equilibrium absolute humidity [kg/kg]

P_{sat} = saturated air pressure [mbar]

P_{atm} = atmospheric air pressure [mbar]

The absolute equilibrium humidity and the absolute outlet humidity of the air must be equal for the layer. If they are not the same, a new estimate for the outlet absolute humidity is made and the mass and energy balances for the bottom layer are repeated.

Once the actual outlet absolute humidity is found for the bottom layer, the outlet conditions are established and become the inlet conditions for the next layer. The mass and energy balances are repeated for each of the grain layers during the time interval. When the top layer is reached, the time is increased by one interval and the procedures described above are repeated.

4.3 THE INSECT-POPULATION GROWTH MODEL

The maize weevil is one of the most damaging pests in Zimbabwe. Detailed studies of the population dynamics of the pest are lacking. Inferences about the maize weevil ecology have been made using basic rice weevil data. To provide some insight into the maize weevil development, a Leslie model is developed to simulate the growth pattern of the maize weevil. The technique for using matrices for age-structured populations was developed by Leslie (1945).

4.3.1 Model Development

The following assumptions are used to develop the maize weevil population growth model:

1. there is no significant migration;
2. low fecundity has more impact on population growth than natural mortality;
3. there is no significant predation;

4. there is no interaction with other pests;
5. adults consume equal amounts of grain per degree day;
6. pupae do not consume grain;
7. adults do not lay eggs when temperatures are below the threshold.

The above assumptions are necessary to develop the model. The numbers of migrating weevils can not be reasonably estimated. The model assumes that the storage facility prevents insect entry.

The rate at which eggs are laid has a more direct impact on the insect population growth. The immature stages of the weevils are hidden in the kernels and are not likely to suffer predation. The model assumes that only maize weevils are the in the grain. There is no conclusive data on the effects of other pests on the maize weevil. It is therefore difficult to simulate that interaction. This assumption is the more serious in that it renders the model inaccurate if other pests are in the bin in large numbers. Adult weevil energy requirements are not likely to vary if conditions remain the same. That is the basis of the fifth assumption. Pupae normally do not consume grain. When temperatures are below the development threshold, most stored-grain pests do not lay eggs.

The parameters considered in the model are described below. The conditions chosen as optimal for maize weevil development are 31°C, 70% relative humidity and 12.5 % grain moisture content (Sinha, 1985).

Hardman (1976) observed that approximately 45.5% of the rice weevil adult population lays eggs. The model assumes that the female weevil lays an average of 300 eggs in 80 days. Each weevil lays 5 eggs per day (Curtis, 1883), and 6.8 eggs per day according to Segrove [1951, as quoted by Longstaff (1981)]. Birch [1945a, as quoted by Hardman (1978)] observed that the rate of fecundity for S. oryzae is also influenced by population density. There is a reduction in oviposition caused by direct disturbance of other adults and also by the diminishing number of kernels available for depositing the eggs. The disturbance is exacerbated by high grain temperatures. Increasing temperatures enhance weevil locomotion.

The model assumes that each female lays 5 eggs per day during 75% of her adult life, and that 45.5% of the adult female population lays eggs.

Oviposition in the field begins when the kernels reach the 'dough' stage or 65% (39% w.b.) (Longstaff,1981). Two larvae may develop in one kernel at the same time or at different times. Weevils use a kernel in which a larva has developed if necessary. However, the model assumes one egg per kernel and 3800 kernels per kilogram.

There is a natural mortality rate at each stage of the insect life cycle. It is low under optimum conditions. External factors have a pronounced effect on mortality. The model has a mortality sub-routine developed by the author which calculates the reduction in population only under sub-optimal conditions.

When no degree-days are accumulated at time (k) (temperature<development threshold), the population is reduced for each stage at time (k+1) as follows:

$$PA_{k+1} = .99\ PA_k + PP_k \tag{35}$$

$$PP_{k+1} = PP_k + PL4_k \tag{36}$$

$$PL4_{k+1} = 0.98\ PL4_k + PL3_k \tag{37}$$

$$PL3_{k+1} = 0.97\ PL3_k + PL2_k \tag{38}$$

$$PL2_{k+1} = 0.96\ PL2_k + PL1_k \tag{39}$$

$$PL1_{k+1} = 0.95\ PL1_k + PE_k \tag{40}$$

$$PE_{k+1} = PE_k + .1\ PA_k \tag{41}$$

where PA = the adult weevil population

PP = the pupae population

PL1 to PL4 = the larval instar populations for stages 1 to 4

PE = the egg population.

The population at time k that is added to each stage is the population growth from that stage to the next (e.g. PP_k is the proportion that develops from pupae to adults weevils in one degree-day).

The newly-hatched larval instar is susceptible to climatically induced mortality. Death increases rapidly as the ambient temperature and relative humidity approach 34°C and 20%, respectively. The same occurs when the temperature and the relative humidity rise to 34.5°C and 100%, respectively; the mortality can be as high as 90% [Birch (1945) as quoted by

Longstaff (1981)].

High temperature and low grain moisture content increase mortality. Large, sudden changes also result in increased mortality even if it is not for a prolonged period of time. Longstaff (1981) compiled data on the time required for S. oryzae to reach 50% mortality under different temperature and relative humidity conditions (see Table 4.1).

The extent of damage to a kernel is determined by the insect species and number, the type of grain, the moisture content and temperature of the grain and the length of storage. Fifty percent of the total kernel (wheat) loss to S. oryzae occurs within the first 9.5 days [White (1953) as quoted by Cotton and Wilbur (1982)]. Weevils consume 30% of the kernel (Curtis, 1883). Kansas State University research (unpublished data) indicates that S. oryzae consume 26% and S. granarius consume 50% of the wheat kernel. Campbell et al. (1976) determined that a larva of S. oryzae destroys 7.35mg. of dry weight and adults consume 3.79mg of dry weight in the first 3 weeks of adult life. Sinha and Campbell (1975) developed a growth curve for S. granarius (see figure 4.1) using the energy content of each insect.

The above information on consumption was used to derive the following relationships:

1. Total larval period = 15 days (260 degree days).

   Degree-days are calculated for i=1 to i=24 :

$$\text{Degree-day} = [\Sigma_{i=1} (\text{Hourly temperature - Threshold temperature})]/24 \qquad (42)$$

2. Consumption over 15 days is 7.35mg.

3. Total adult period = 80 days (357 degree days).

4. Number of degree days per calendar day = 16.

It is also assumed that under optimum conditions each stage takes the shortest time to develop, and that 16 degree-days are accumulated per calendar day (422.7 degree days / 26 calendar days.

The number of degree-days varies from day to day. In order to establish development rates, a figure had to be assumed.

Other specific figures on the rice weevil (Sinha and Campbell, 1975) that are assumed: (1) the first larval instar consumes 0.35mg; (2) the second larval instar consumes 1.0 mg; (3) the third larval instar consumes 1.5mg; (4) the fourth larval instar consumes 4.5mg; and (5) the adult consumes 3.7mg. Thus:

TOTAL CONSUMPTION PER DEGREE DAY =

{ (#L1 * 0.35/260) + (#L2 * 1/260) + (#L3 * 1.5/260)

+ (#L4 * 4.5/260) + (#A * 3.79/357) } * 0.001g (43)

where: L1 - L4 = 1st to 4th larval instars

A = Adult.

Stored-grain insects contaminate more grain than they eat (Wilbur and Mills, 1985) because of:

1. The presence of dead or living insects (eggs to adults)

Table 4.1 Period (in weeks) required for <u>Sitophilus Oryzae</u> to incur 50% mortality.

Source	Temperature (^{o}C)	Relative Humidity (%) 45	55	70
1	15	-	-	51
1	18	16	-	32
1	21	12.7	-	14
2	24	-	21	25
1	27	10.8	-	22
2	27	-	16	28
3	29.1	-	-	17
2	30	-	20	-
2	32.3	8.3	12	16
3	-	-	-	12
2	33	-	-	13
3	34	8	-	11

Adapted from Longstaff (1981)

Sources:
1. Evans (1977a) and unpublished data
2. Longstaff (1981) unpublished data
3. Birch (1953a)

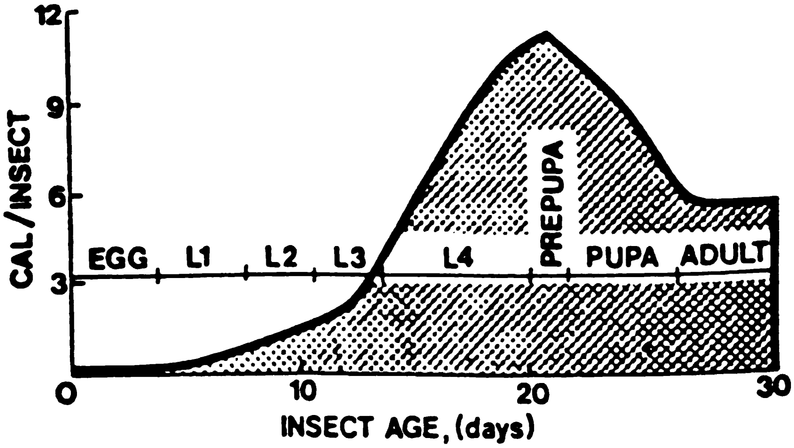

Figure 4.2 Growth curve of an average granary weevil in terms of its energy content reared at 30°C and 70% RH (Sinha and Campbell, 1975).

and insect parts.

2. The presence of cast exoskeletons, egg shells and pupal cases.

3. The presence of fecal materials.

It is not economical to remove all the contaminants by cleaning. Grain dust which consists of flour, excrement and broken kernels is part of the grain loss. Larvae of S. oryzae produce 1.67 mg of dry dust and an adult produces 0.398 mg (Campbell et al., 1976). The model assumes that the maize weevil S. zeamais development stages produce the same amounts of frass under optimal conditions. The frass production is:

FRASS PRODUCTION PER DEGREE DAY =

$$((\#L1 * 0.08/260) + (\#L2 * 0.23/260) + (\#L3 * 0.34/260) + (\#L4 * 1.02/260) + (A * 0.398/357)) * 0.001gm \qquad (44)$$

The frass production is proportional to the amount of grain consumed per degree-day. Of course, frass contributes to the amount of dust generated in the storage facility when the grain is handled.

The model estimates the infestation levels using the following equation:

$$\text{Infestation (\%)} = \frac{\#\ \text{infested kernels}}{38000 * \text{amount of corn}} \qquad (45)$$

where # of infested kernels = Initial (egg pop.+ L1 pop.+L2 pop. + L3 pop. + L4 pop. + pupa pop. + ΔP (eggs + L1 + L2 + L3 + L4 + pupa) at time k ;

and ΔP is the positive gain in population (e.g. $\Delta P_{eggs} = Eggs_{k+1} - Eggs_k$). If there is a decay, a value of zero is used to show that there is no gain but the infestation level does not drop.

The amount of corn is expressed in metric tonnes. The infestation equation assumes that adults do not infest the grain since they live outside the kernels once they have emerged. In reality, the quality is reduced by the very presence of live or dead adults in the grain.

Equations 43 - 46 are affected by temperature, moisture content of the grain and relative humidity. The effect of the relative humidity of the surrounding air and the initial moisture content of the grain is calculated by multipying the values for each parameter by several coefficients obtained from look-up tables. The model generates the tables using the relationships in tables 4.2 and 4.3. The coefficients are used in the calculation of degree days. Thus:

$$\text{Degree-day} = \{[\Sigma_{i=1} (\text{Hourly temperature} - \text{Threshold temperature})]/24\} * \text{moisture content coefficient} * \text{RH coefficient} \quad (46)$$

Using degree-days as the basis for the calculations incorporates the effect of temperature on each parameter.

Assuming that under optimal conditions each stage requires the minimum time to develop, Table 4.4 was compiled.

Table 4.2 Coefficients for grain moisture content (in equation 46).

Moisture Content (%)	Coefficient Equation
>5 to <10	0.4 + .1 x (M.C. - 9)
10 to <11	0.5 + .2 x (M.C. - 10)
11 to <12	0.7 + .3 x (M.C. - 10)
12 to <13	1.0
13 to <14	1.0 - .1 x (M.C. - 13)
14 to <15	0.9 - .1 x (M.C. - 14)
15 to <23	0.8 - .1 x (M.C.- 15)

Table 4.3 Coefficients for average relative humidity (in equation 46).

R.H. (%)	Coefficient Equation
<45	0.5 x (AVG RH)/45
45 to <55	0.5 + .2 x (AVG RH - 45)/10
55 to <65	0.7 + .3 x (AVG RH - 55)/10
65 to <75	1.0
75 to <85	1.0 - .2 x (AVG RH - 75)/10
85 and above	0.8 - .2 x (AVG RH - 85)/15

Table 4.4 Data * for the development of Sitophilus Zeamais (in the Leslie matrix)

Stage	Duration Calendar days	Duration Degree days	Dev. Rate 1/Degree days
Egg to larva 1	5	80	1/80
Larva 1 to larva 2	4	65	1/65
Larva 2 to larva 3	4	65	1/65
Larva 3 to larva 4	4	65	1/65
Larva 4 to pupa	4	65	1/65
Pupa to adult	5	80	1/80
Adult to death	80	1360	1/1360

* The data was compiled from biological information presented in section 3.5 .

The Leslie Matrix for development without mortality in the pre-adult stage is equal to

$$x\,(k + 1) = A\,x\,(k)$$

where A is the matrix of coefficients and x(k) is the population vector for each stage as shown below; k is the discrete time of one degree day. Thus:

$$\underbrace{\begin{bmatrix} 79/80 & 0 & 0 & 0 & 0 & 0 & 1/10 \\ 1/80 & 64/65 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1/65 & 64/65 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1/65 & 64/65 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/65 & 64/65 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/65 & 64/65 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/25 & 1359/1360 \end{bmatrix}}_{A} \quad \underbrace{\begin{bmatrix} \text{egg} \\ \text{larva 1} \\ \text{larva 2} \\ \text{larva 3} \\ \text{larva 4} \\ \text{pupa} \\ \text{Adult} \end{bmatrix}}_{x(k)}$$

The growth coefficients (see table 4.4) are used to determine the survivor coefficients. 1/80 of the eggs develop into the first larval instar per degree-day; 79/80 remain as eggs. A similar calculation is used for the other stages. The coefficients for the number of eggs laid per degree-day is calculated as follows:

$$0.75 * 0.455 * 5/16 = 1/10$$

where 0.75 = the lifetime proportion of active egg laying
0.455 = the number of females laying eggs
5/16 = five eggs per calendar day (16 degree-days).

4.4 THE GRAIN STORAGE SYSTEM MODEL

The grain storage sytem model is the combination of the aeration and maize weevil population growth models.

Combination of the fixed-bed and the maize weevil population growth model was not possible because preliminary tests showed that the fixed-bed model was unstable at low low inlet air temperatures. The possible reason why the use of low temperatures with the fixed-bed model was not accurate is that the thin-layer equation in the model is not suitable for low temperatures.

AERATE is appropriate for chilling grain at low air velocities (< 0.02 m/s) and was therefore used.

4.4.1 Model inputs/outputs

4.4.1.1 Detected number of insects (7 stages)

It is assumed that the number of insects of each development stage can be determined at the time the grain is stored. The number of insects in each stage depends on the time at which the grain is harvested. Late harvested grain will have more insects in the advanced stages of development than earlier harvested grain.

4.4.1.2 Grain parameters

AERATE calculates resistance to the airflow, air velocity through the grain, and static pressure of a specific fan for the following crops: wheat (hard and soft), maize, rye, barley, oats and rice (rough). The program requires initial moisture content, temperature and bulk density of the grain.

4.4.1.3 Weather data

The simulation of aeration and insect population growth with the system model utilizes actual weather data. Weather data for a typical year in Zimbabwe (Bulawayo, 1978) is used. Only the hourly temperature and relative humidity values are needed along with the local barometric pressure. The model has the necessary in-built psychometric subroutines which calculate the air properties.

The program asks for a starting date and length of the simulation. The length of each simulation can be controlled by entering the stopping date or the desired final grain temperature or moisture content in the top layer.

In the chilling operation, it is assumed that the inlet air temperature and relative humidity are supplied by the grain cooling unit independent of the ambient conditions. The cooling air temperature and relative humidity remain constant.

4.4.1.4 Bin parameters

Bin parameters such as the bin depth and floor area required for a given volume of grain can be varied. The fan power and efficiency are selected, and are used to calculate the required air velocity.

4.4.1.5 Data output

The program writes the data on a file or displays the data on a computer screen. The output for the first twenty four hours on the first day of a chilling operation are shown in appendix 4;

the data includes the grain temperature and moisture contents, the air temperature and absolute humidities, and the insect infestation in terms of numbers of insects per stage per level.

CHAPTER V

EXPERIMENTATION

The experiment is carried out at a farm in Williamston, MI (i.e. the Jorgensen Farms).

5.1 THE TEST BIN

The test bin is made of steel and has the following dimensions:

a) height to the eaves = 10.40 m;

b) grain depth = 10.29 m;

c) cross sectional area = 79.46 m^2;

d) bin volume = 818 m^3;

e) approximate grain mass = 607 metric tonnes.

The grain at the peak is slightly above 10.29m. The bin has a fixed inlet leg, a sweep discharge auger and a full false floor.

The full-bin airflow is 0.016 $m^3/m^2/s$ at a static pressure of 1665Pa (the Granifrigor fan curve) and the design airflow using Shedd equation is 0.019$m^3/m^2/s$ at a static pressure of 250Pa.

The variables that are monitored are:

a) grain moisture content

b) grain temperature

c) insect pests

d) stress cracks

e) molds

f) power consumption.

This thesis will discuss the first three variables in detail but the data for insect pests will not be available for inclusion because of the limited storage at the time of this writing.

5.2 MOISTURE CONTENT

The chilling unit (Granifrigor KK140) is tested using grain between 17 and 18% moisture content (w.b). Two kilogram samples are taken every half hour as the bin is filled. Half of the samples are placed in zip-loc bags and taken to the laboratory for moisture content determination using the ASAE standard oven method (ASAE S352.1) (100g at 103^{o}C for 72 hours). The other half is tested using a Burrows digital moisture meter (model 700).

The grain moisture is monitored throughout the test period by taking samples using the standard technique (Barak and Harein, 1981); four vertical trier samples are taken along the N-S line across the bin, one horizontal trier sample of the surface grain, and several deep probe samples at the center of the bin.

These samples are tested for insect pests, stress cracks and molds in the laboratory before drying on an ambient test dryer to 13.5 - 14.5% (w.b) moisture content.

5.3 TEMPERATURE

The grain temperatures in the bin are monitored using a

A

B

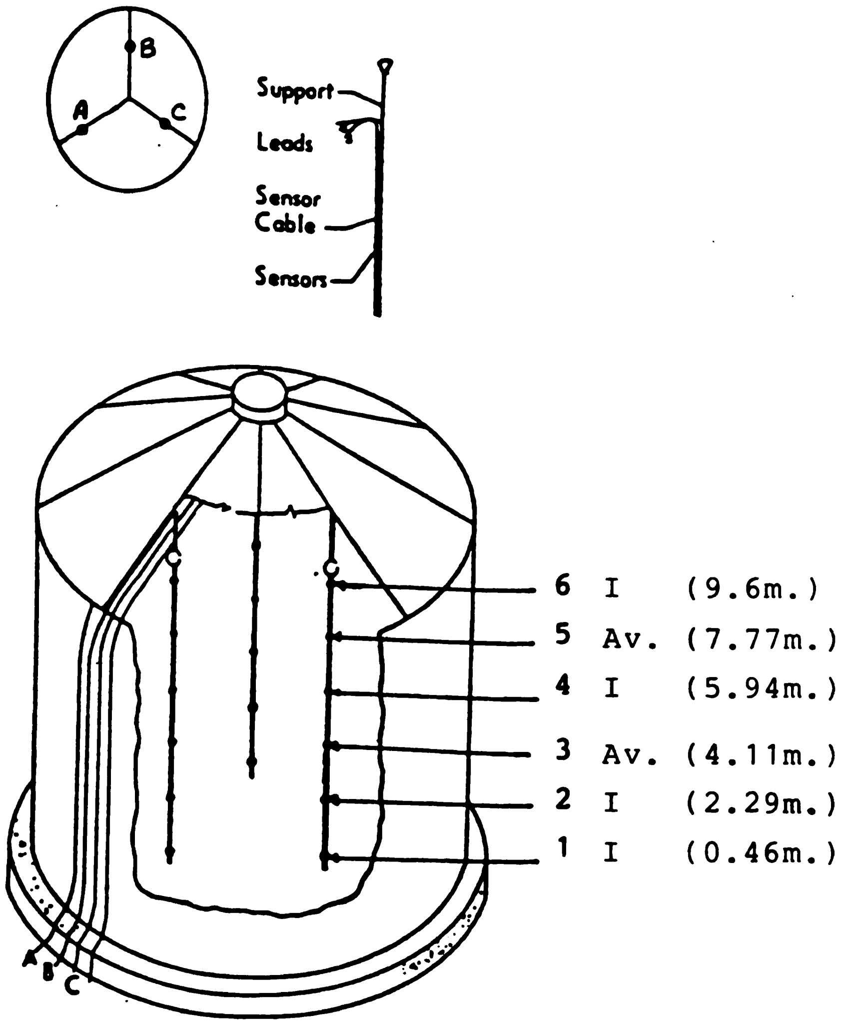

Figure 5.1 Bin temperature sensing system.

Rolfes temperature detection system. The system is comprised of thermocouples suspended on cables as described in appendix B. The cables are arranged in a triangle as shown in figure 5.1A. The temperature sensors on the cables are located as shown in figure 5.1B. The thermocouple wires are connected to the data acquisition system. The temperatures at the different layers are either monitored individually (I) or are averaged (Av) (see figure 5.1B). The wet and dry bulb temperatures at the inlet and outlet of the chilling unit are measured and the relative humidity of the air entering the chilling unit and the bin are calculated.

5.4 INSECTS

The insects infestation is monitored using GrainGuard traps (see figure 5.2)(GrainGuard, Verona,WI 53593). Fifteen traps are placed in the control bin and eight in the test bin. Eleven traps are placed in the control bin at 0.2m and four at 0.75m depths as shown in figure 5.3A. The test bin has seven traps at 0.2m depth and one at 0.75m. Comparisons between the two bins are for the traps at equivalent positions only. The traps are checked once a week. The frequency is reduced to once every fortnight if no insects are observed in the first twelve weeks of sampling. Probe samples are also taken at each trap site to determine any moisture content changes.

5.5 DATA ACQUISITION

A menu-driven Hewlett Packard data acquisition unit is used to collect the temperature data (see figure 5.4). The HP85 records the data as it is processed by the HP3054DL. The system

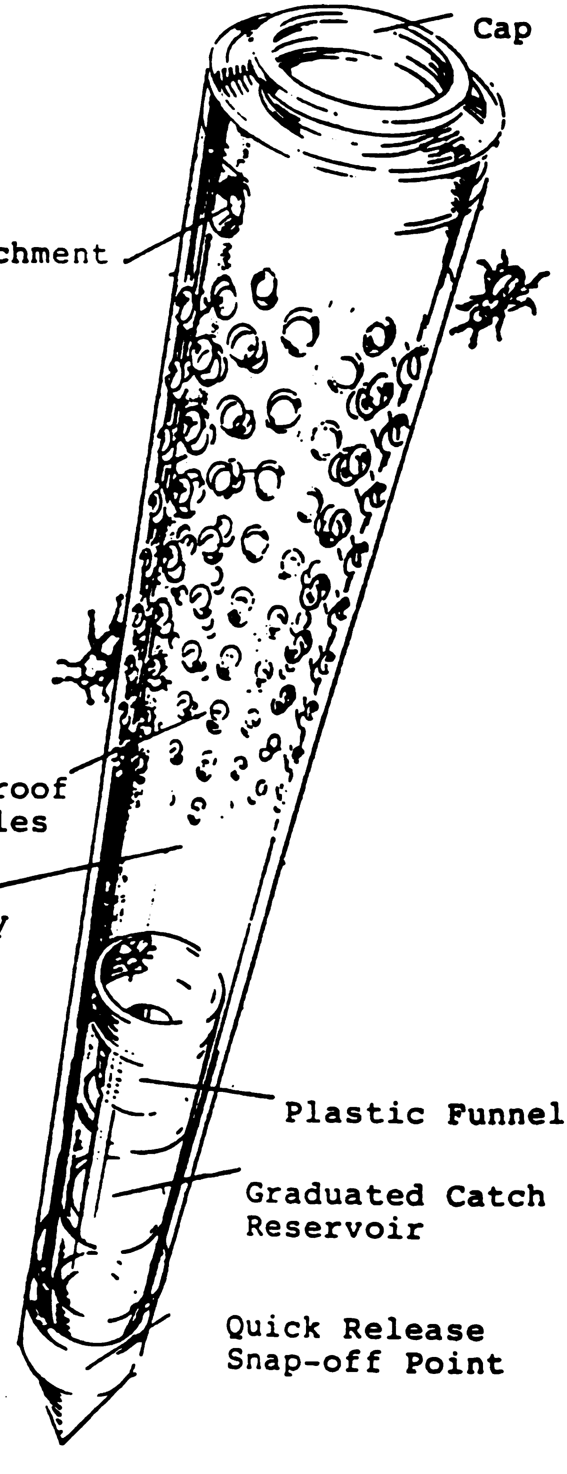

Figure 5.2 GrainGuard trap.

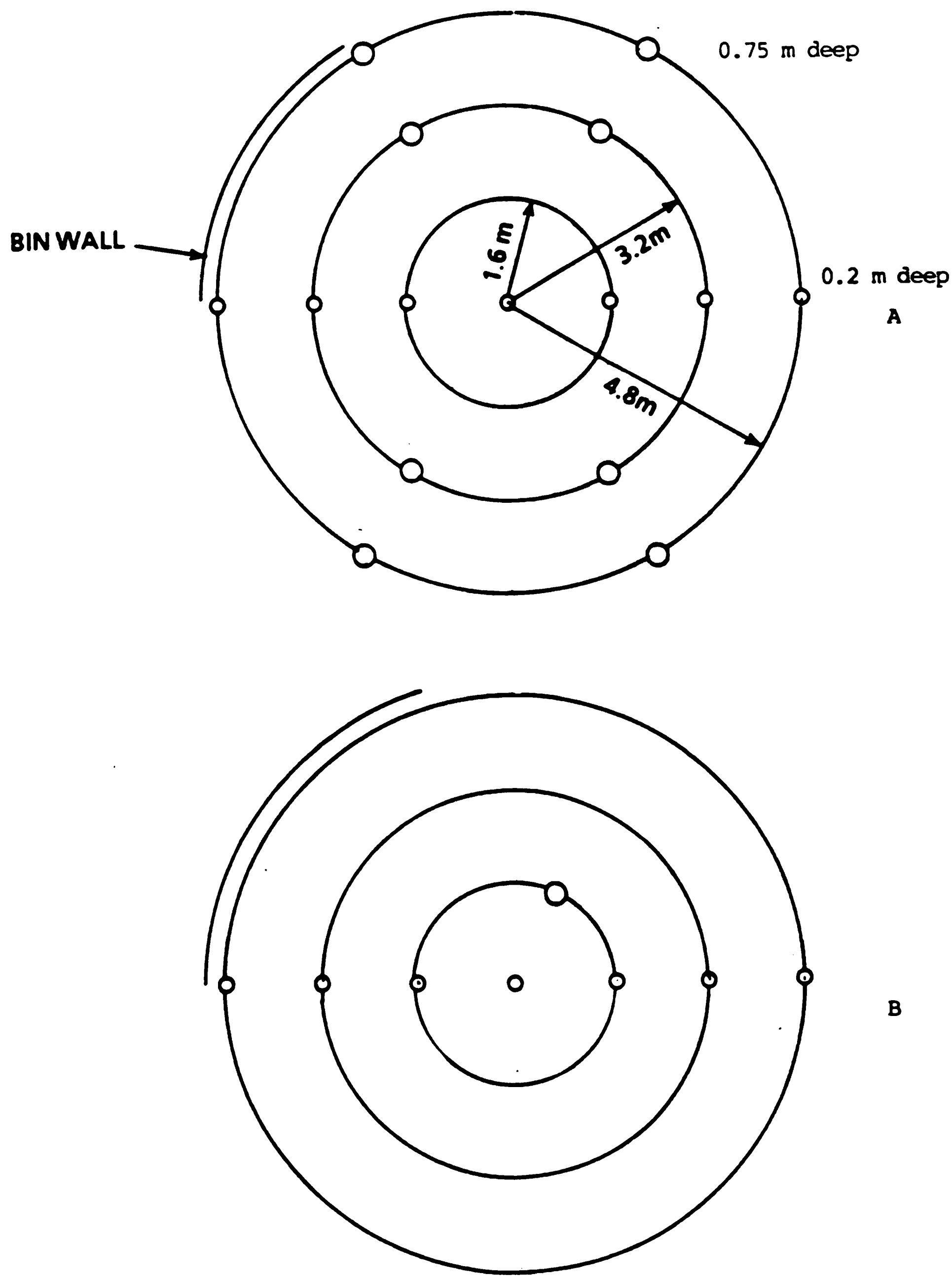

Figure 5.3 Layout of traps in the control bin (A) and the test bin (B).

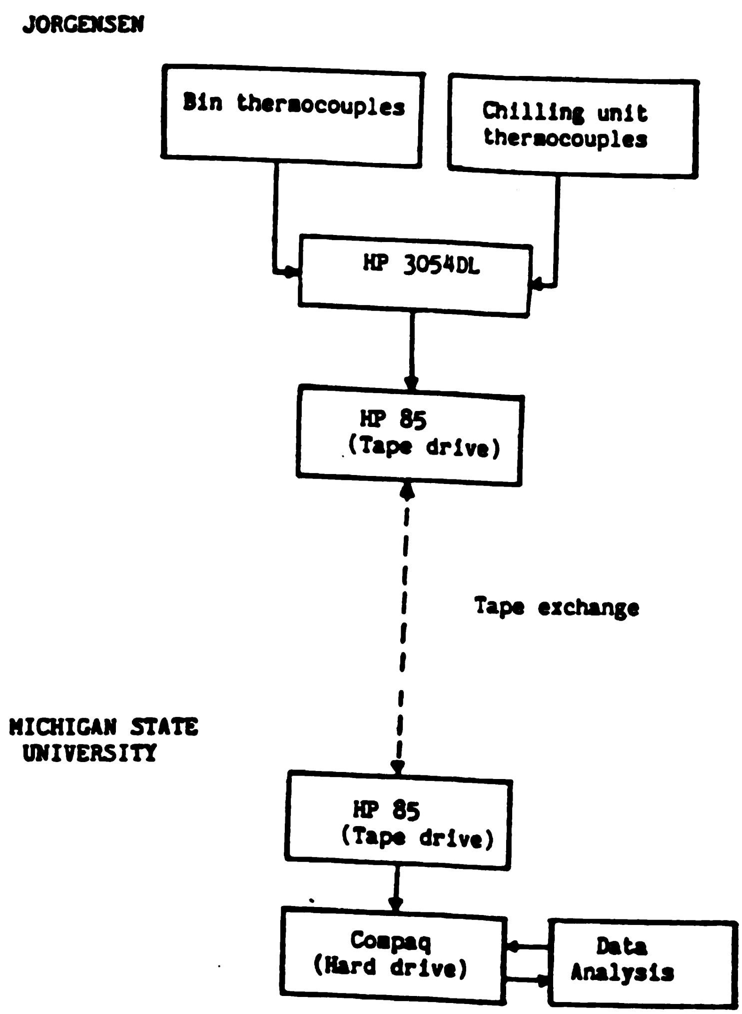

Figure 5.4 Data Acquisition

utilizes two cartridges; the first carries the program menus written in BASIC and the second is the data cartridge. The main program is called "autost" (automatic start). The autostart routine permits the computer to load and run the program without further operator instructions. After the computer is programmed (booted) to operate, a menu similar to the one in table 9 is displayed. Four special function keys are used to program new data logging operations. The keys on the keyboard are not displayed on the screen but are shown in table 5.1 for clarity. Each special function key has a help menu.

5.5.1 Channels

The "Channels" menu is used to set the number of channels from which the data is input. In this case, the setting is 0-18 for T type thermocouples. The instructions to the computer are saved on the data tape in a file. The temperature limits are set during channel set-up.

5.5.2 Timing

The "Timing" menu records the starting time, the date, the filename of the channel set-up, and the interval between readings. The instructions form a short basic program and are saved under the name "timing" on the data tape.

5.5.3 Initialization

The initialization process carries out two main functions; it reserves a file for the data and creates a place file. The data file has space for 636 records which is equivalent to about 318 or 636 hours (every half hour or hour, respectively) of data recording for the Jorgensen project. The place file keeps track of the scanning, and allows the program to continue where it stopped (e.g after a power failure).

The final task is to save the run program as "autost" on the data tape. The average temperatures are collected by looping the thermocouples together as shown in figure 5.5.

The data that is recorded is transferred from the tapes to a hard disk on the computer for manipulation and analysis. A special communication program written in Fortran used for this purpose.

Table 5.1 HP3054DL set-up menu.

HELP........	Print out instructions and useful data
CHANNELS....	Enter channels, Functions, User labels, linearization, Limits, Actions
TIMING......	Set start time, Interval, Monitor channels, Print and Record channels
RUN.........	Return to Menu or start the logger

HELP	CHANNELS	TIMING	RUN
K1	K2	K3	K4

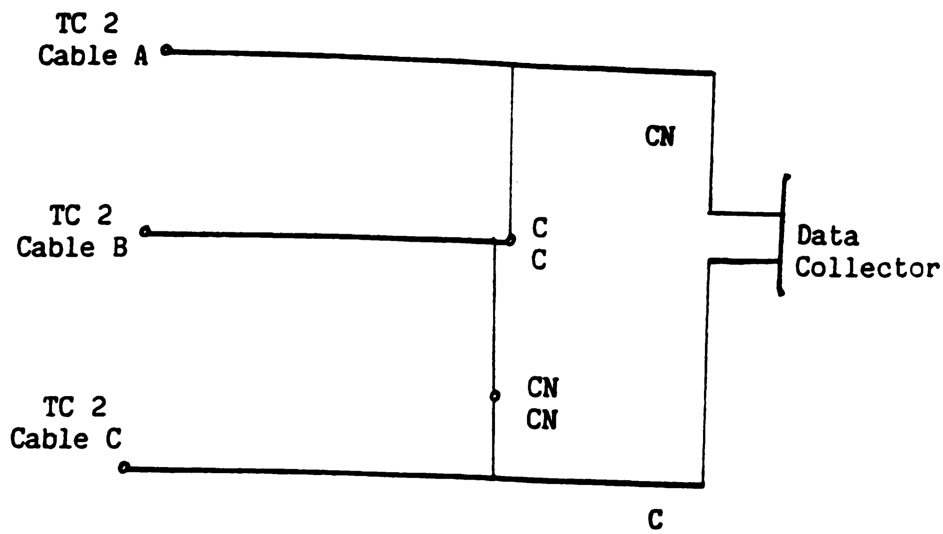

Figure 5.5 Looping thermocouples to record average temperature recorded by three thermocouples.

TC = Thermocouple
C = Copper wire
CN = Constantin wire

CHAPTER VI

RESULTS AND DISCUSSION

6.1 SIMULATION

6.1.1 Maize weevil population growth model in Zimbabwe

The maize weevil population growth model was tested under typical conditions experienced in Zimbabwe (see table 6.1) before it was combined with the aeration/chilling model.

Maize is normally stored at 11% moisture content in Zimbabwe (12.5% is the maximum accepted). It is important to evaluate the insect population changes in a normal year. Table 6.2 shows the population change (individual insects in 100 metric tonnes) over a thirty week period. The data is also graphically presented in figures 6.1 - 6.5.

The egg population increases rapidly starting at the thirteenth week (see figure 6.1). The population of the first larval instar rises at about the same time but at a lower rate (see figure 6.2). The low temperatures cause the high mortality of larvae from week 5 to 12. The effect of temperature and relative humidity is also evident in the decreases in population in weeks 19 to 20 and 24 to 25. Figure 6.3 shows a time lag of 3,4 and 9 weeks before the second, third and fourth larval instars, respectively, show an increase. The pupa and adult

Table 6.1 Combinations of variables used in the simulation.

Combination	Storage start	Temperature factor *	Grain m.c % w.b.
Early Hot Wet (EHW)	May 1	1.15	13
Early Hot Dry (EHD)	May 1	1.15	11
Early Cool Wet (ECW)	May 1	0.85	13
Early Cool Dry (ECD)	May 1	0.85	11
Late Cool Dry (LCD)	August 1	0.85	11
Late Hot Dry (LHD)	August 1	1.15	11
Late Cool Wet (LCW)	August 1	0.85	13
Late Hot Wet (LHW)	August 1	1.15	13
Early Normal Wet (ENW)	May 1	1.00	13
Early Normal Dry (END)	May 1	1.00	11
Early Cool Normal (ECN)	May 1	0.85	12
Early Hot Normal (EHN)	May 1	1.15	12

* Actual weather data for 1978 (Bulawayo-Zimbabwe) is considered to be "normal" weather with a temperature factor of 1.0. This factor is increased or reduced by 15% to reflect a warmer or colder than normal year, respectively; the absolute humidity is kept constant.

Table 6.2 The maize weevil population (individual insects) change with time in 11% maize stored 1 - 30 weeks under normal Zimbabwe weather conditions.

End of week	Eggs	Larval instars 1	2	3	4	Pupa	Adult
1	189.0	102.0	100.0	100.0	100.0	103.0	112.0
2	288.0	116.0	101.0	100.0	100.0	105.0	125.0
3	379.0	138.0	105.0	100.0	100.0	107.0	138.0
4	437.0	153.0	105.0	98.0	98.0	109.0	146.0
5	479.0	163.0	103.0	93.0	94.0	109.0	152.0
6	431.0	135.0	83.0	76.0	81.0	107.0	148.0
7	449.0	139.0	79.0	70.0	75.0	105.0	151.0
8	419.0	123.0	68.0	59.0	65.0	103.0	149.0
9	423.0	122.0	63.0	53.0	59.0	99.0	150.0
10	381.0	106.0	53.0	44.0	50.0	95.0	145.0
11	358.0	97.0	47.0	37.0	44.0	91.0	142.0
12	366.0	99.0	45.0	38.0	39.0	87.0	143.0
13	434.0	122.0	52.0	35.0	39.0	83.0	149.0
14	510.0	152.0	61.0	38.0	39.0	80.0	156.0
15	602.0	194.0	77.0	42.0	39.0	76.0	165.0
16	726.0	262.0	106.0	51.0	40.0	72.0	176.0
17	811.0	313.0	132.0	61.0	42.0	69.0	184.0
18	932.0	395.0	178.0	80.0	48.0	67.0	194.0
19	1017.0	457.0	216.0	98.0	54.0	66.0	202.0
20	1030.0	452.0	229.0	109.0	59.0	66.0	202.0
21	1188.0	582.0	312.0	155.0	79.0	71.0	217.0
22	1359.0	728.0	423.0	224.0	115.0	83.0	237.0
23	1532.0	872.0	545.0	307.0	163.0	107.0	262.0
24	1627.0	946.0	611.0	356.0	194.0	124.0	278.0
25	1737.0	1028.0	684.0	413.0	231.0	146.0	298.0
26	1780.0	1008.0	694.0	439.0	257.0	168.0	313.0
27	1973.0	1111.0	780.0	517.0	319.0	215.0	358.0
28	2235.0	1277.0	895.0	606.0	386.0	266.0	414.0
29	2606.0	1490.0	1046.0	719.0	472.0	333.0	496.0
30	3206.0	1814.0	1272.0	883.0	595.0	435.0	626.0

Conditions:

a) moisture content 11% w.b.
b) development threshold 12.6 ^{o}C
c) temperature factor 1.00
d) initial population per stage 100.0
e) start of storage May 1.

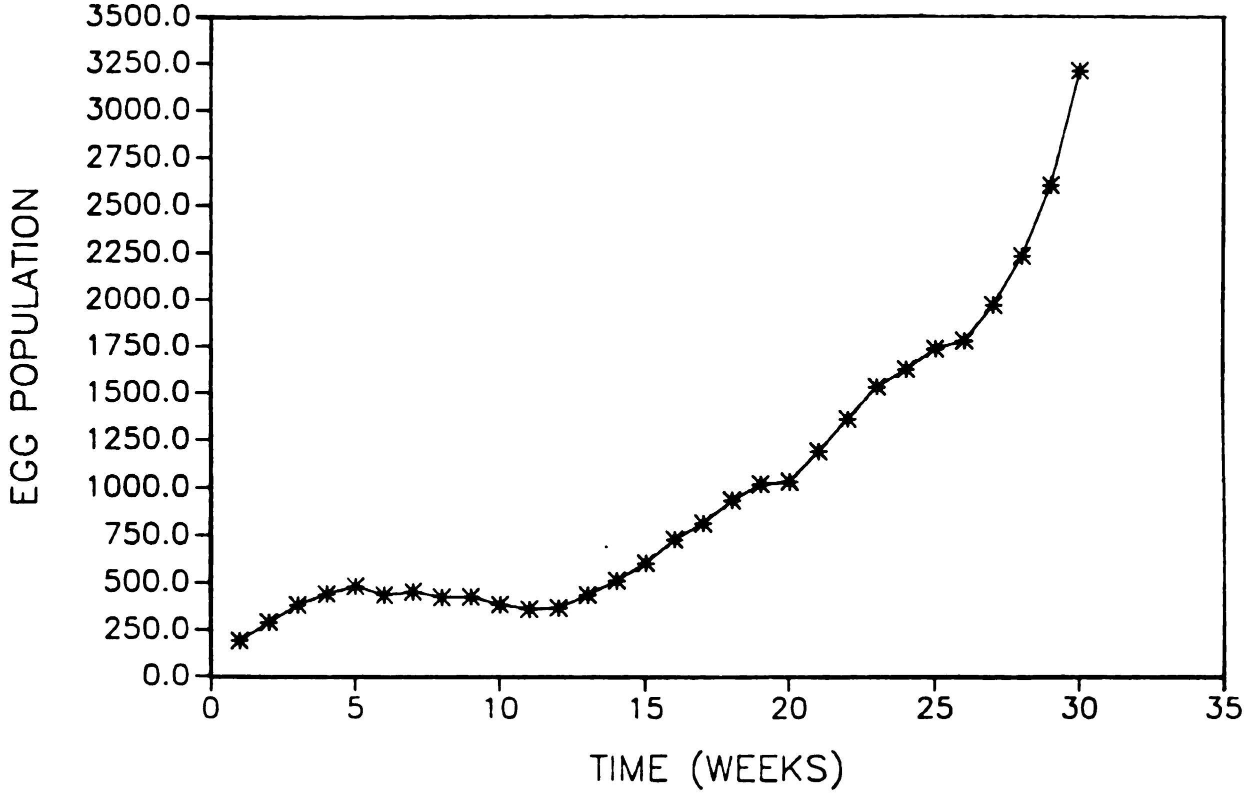

Fig 6.1 Egg population change with time; moisture content is 11%; storage began on May 1 in a normal year

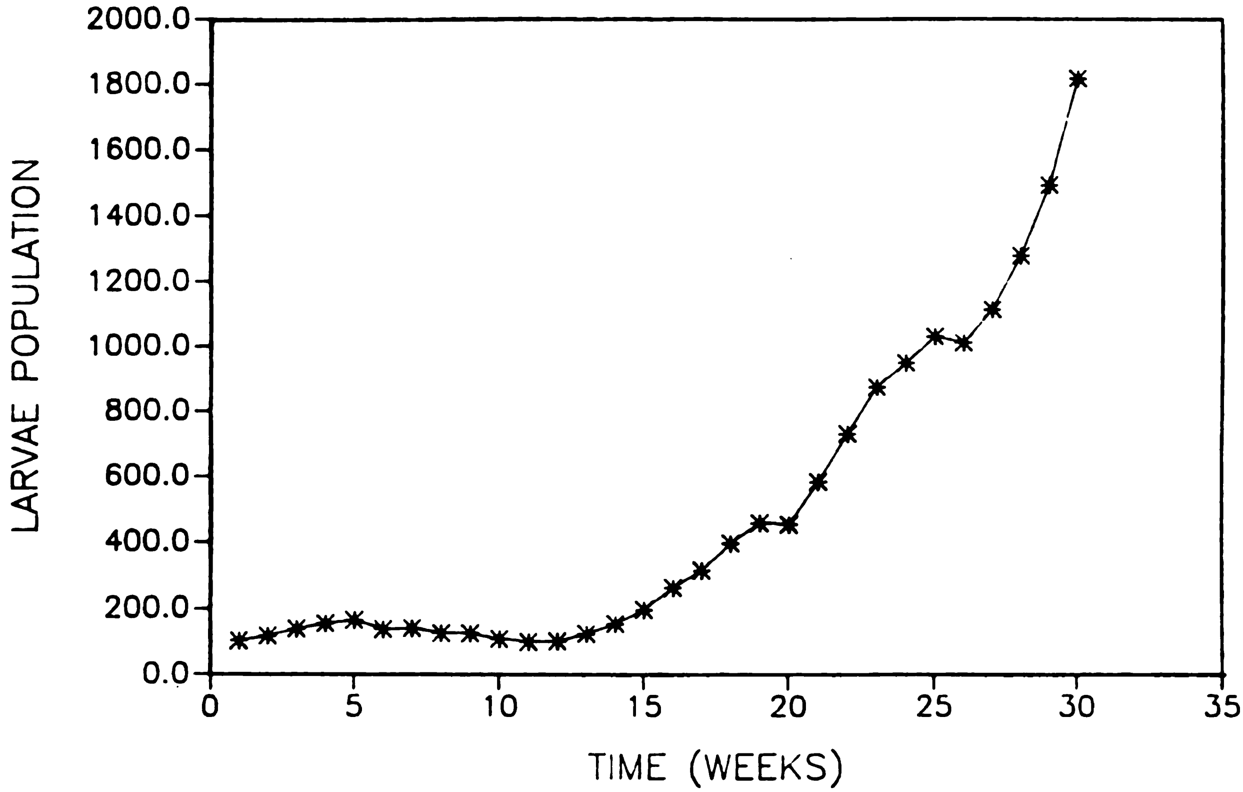

Fig 6.2 First larval instar population change with time; moisture content is 11%; storage began on May 1 in a normal year

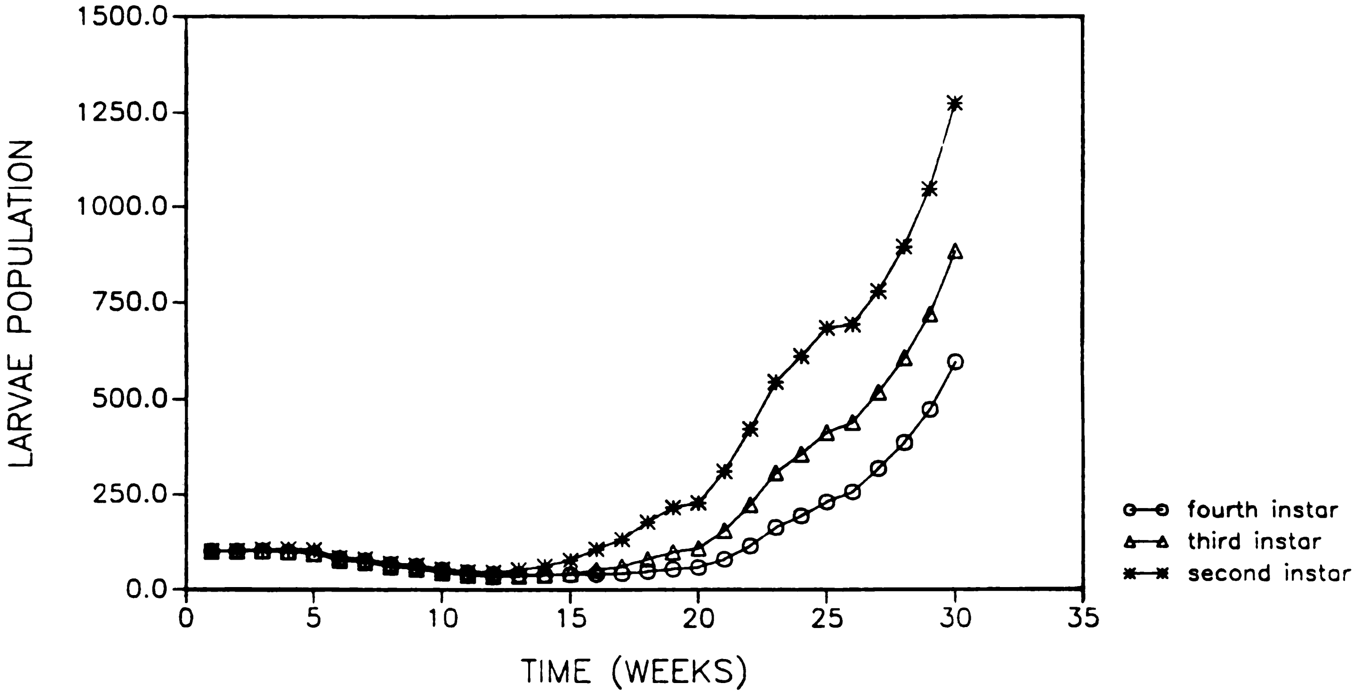

Fig 6.3 Second,third & fourth larval instar population change with time; m.c.is 11%; storage began on May 1 in a normal year.

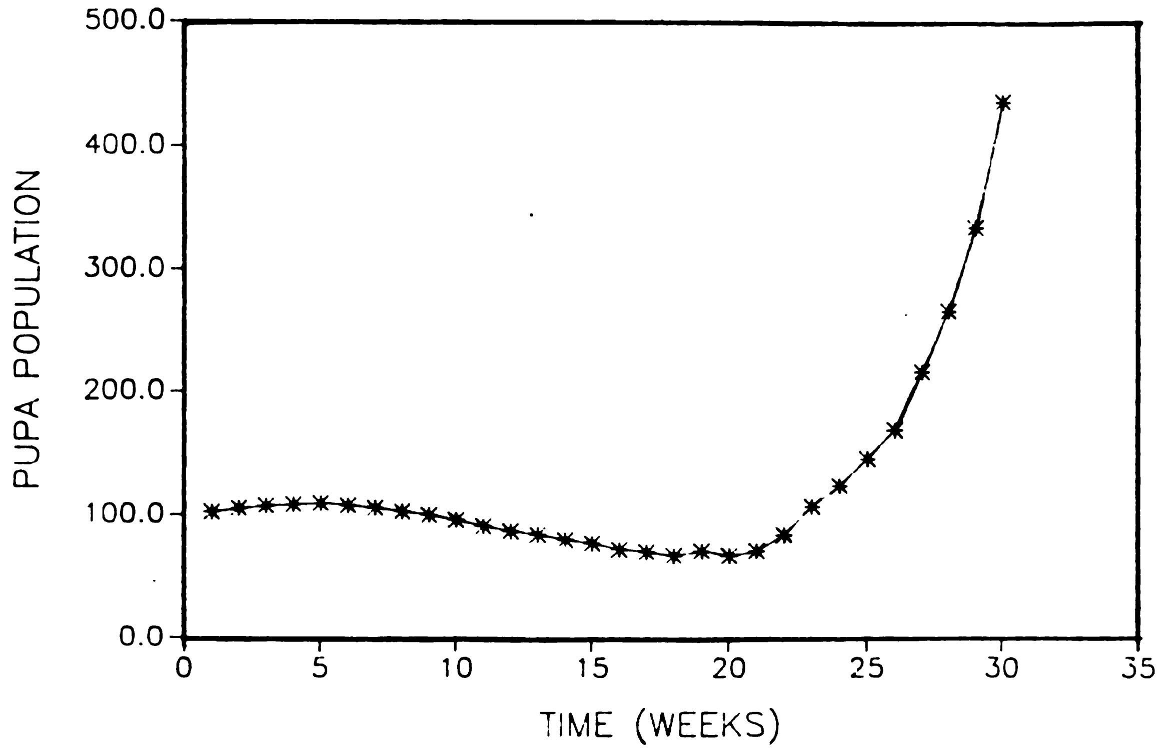

Fig 6.4 Pupa population change with time; moisture content is 11%; storage began on May 1 in a normal year

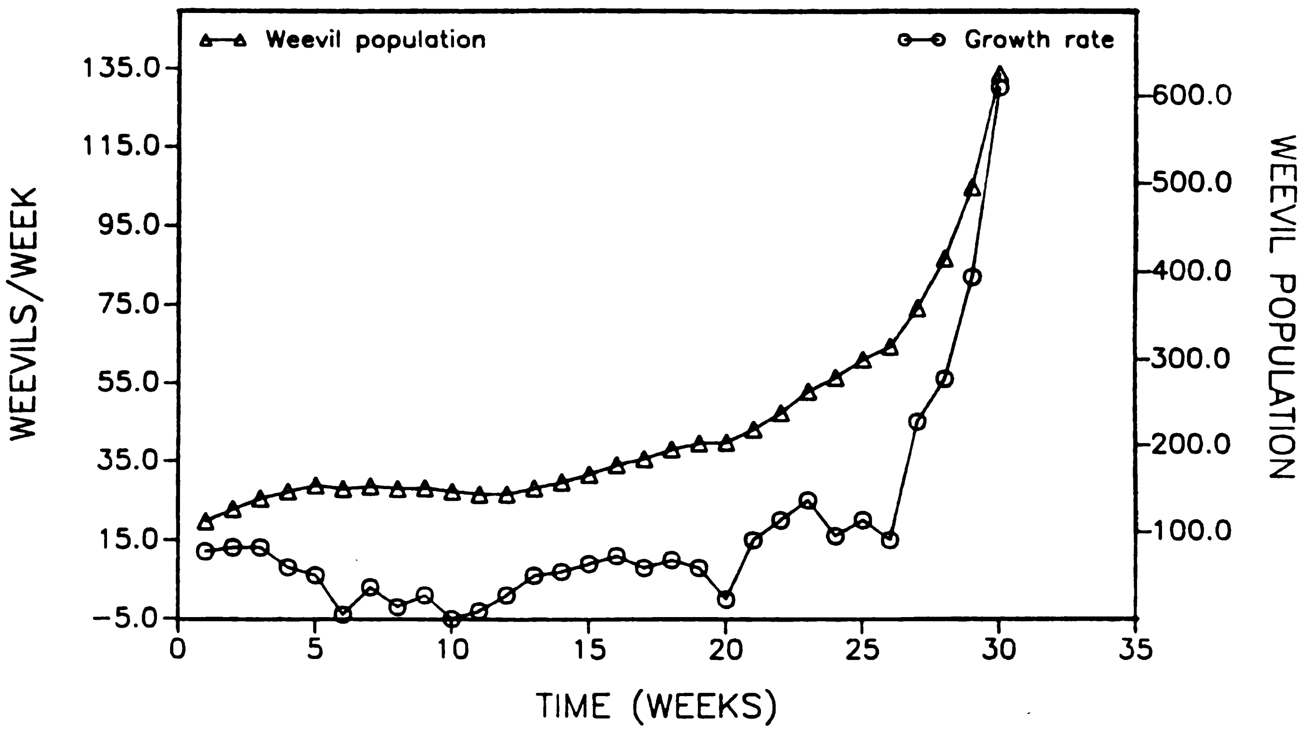

Fig 6.5 Adult weevil population and rate change with time; moisture content is 11%; storage began on May 1 in a normal year

populations increase sharply after about twenty weeks (see figures 6.4 and 6.5). Figure 6.5 also illustrates the rate of population increase per week. The curve shows the response of the population to ambient conditions. The mortality is high at the times when the temperature falls below 5^{o}C and low from October.

The graphical information should be very useful to storage managers. The manager who wants to minimize the maize infestation with weevil eggs should implement control measures at week eleven. If however, he/she is less concerned about the egg population, he/she will either sell the grain or apply insect control measures by the fourteenth week to have the minimum damage.

If an infestation level of ten live insects per 1000g (sample grade) is considered critical , action has to be taken when the total number of insects reaches one million per hundred tonnes.

In order to determine the effect of a change in the model parameters, one parameter value was changed, with all other conditions held constant. The combination of parameters is given in table 6.1. Seven months (May to November) are simulated initially. The population trend becomes clear after thirteen weeks. More tests are conducted for thirteen week periods under different conditions (see appendix E)

Storage starting on May 1 is considered "early" and storage beginning on August 1 is "late". For clarity and ready comparison, each graph shows four curves.

The model computes the population of each stage. The development of eggs, the fourth larval instar and the number of adults are analysed in detail. The egg population change is rapid. The changes in the first, second and third larval instar populations for storage starting on May 1 are shown in figures 6.1 to 6.5 and are less voracious than the fourth larval instar. And, the adult population reflects the potential for reproduction and increased infestation.

If the maize is stored on August 1 at 11% moisture content (LCD) in a cooler than normal year, the egg population increases gradually to about nine times the initial population (see figure 6.6). When 2% (LCW) wetter grain is stored under the same conditions, the egg population increases fourteen times. If grain similar to the grain used in the above tests (LCD and LCW) is stored in a warmer than usual year, the egg population increases eighteen and thirty one times more rapidly than in the grain stored in normal year, respectively.

Figure 6.7 shows how low temperature limits insect egg production. The temperatures in Zimbabwe are lowest in June and July, and increase in August. The same grain and temperature conditions employed in figure 6.6 are used but the test begins on May 1. The highest increase in the egg population is about eighteen times if the grain is stored in a warmer than normal year. In cooler than normal conditions, the egg population increases only two and half times in the wet grain (13%) and decays for the grain at 11% moisture content.

Larvae are also susceptible to moisture and temperature

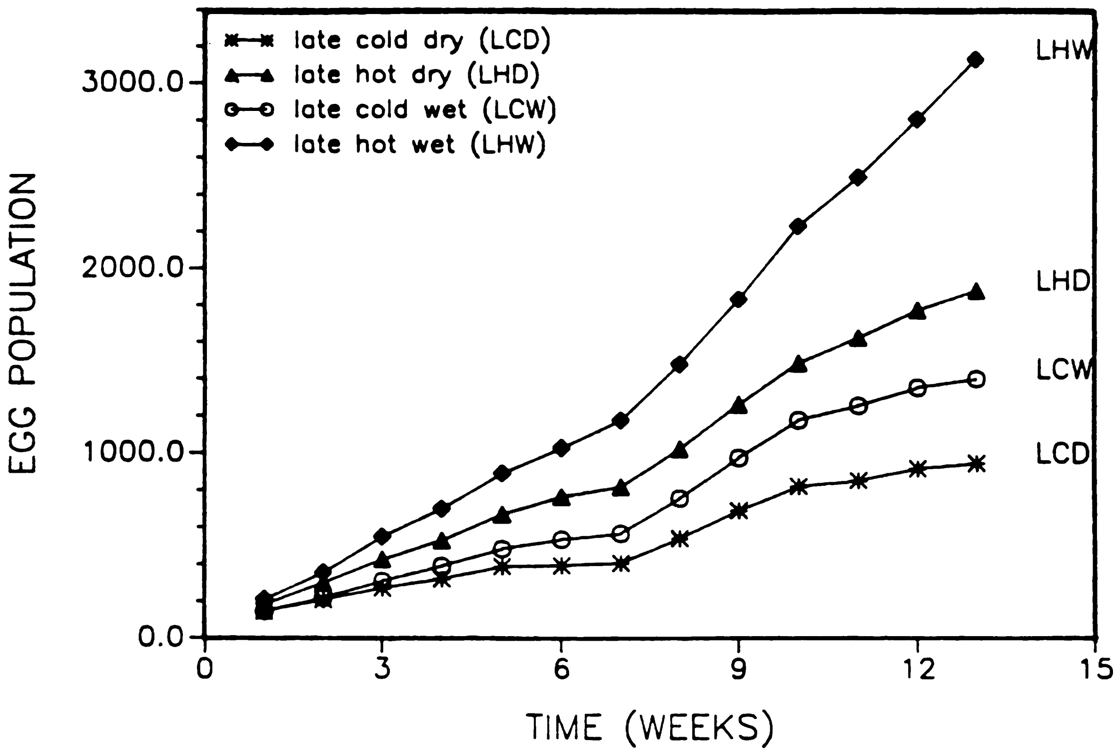

Fig 6.6 Egg population change with time under different conditions; storage began on August 1

changes (see figure 6.8). Larvae in grain stored on August 1 at 11% moisture content in a cool year (LCD) suffer a high mortality. Larvae in wetter grain at the same temperature conditions (LCW) increase in number slightly. If the weather is warmer, the mortality is reduced in both the dry (LHD) and wet grain (LCW). The fourth larval instar population increases two-fold and five-fold compared to LCD and LCW, respectively. Significant increases are evident in the seventh week.

Larvae in grain stored in a cool year at 12% moisture content (ECN) experience continuous mortality (see figure 6.9). A similar but reduced mortality is suffered by the larvae in 12% (END) and 13% (ENW) moisture content grain stored under normal temperature conditions. If the year is warmer (EHN), the larvae population suffers high mortality but the higher temperatures result in only a small population increase.

The adult population is not very susceptible to low temperatures. The slow increase in population is partly due to the low development rate and partially the effect of temperature and moisture content.

When the weevils are living in 11% moisture content grain,and are placed in storage on August 1 in a cool year (LCD), the increase in population is not significant (see figure 6.10). The population only doubles in the wet grain (LCW) in thirteen weeks. If the grain at 11% moisture content is stored at higher temperature conditions (LHD), the insect population more than triples. The population increases about six times if the grain is

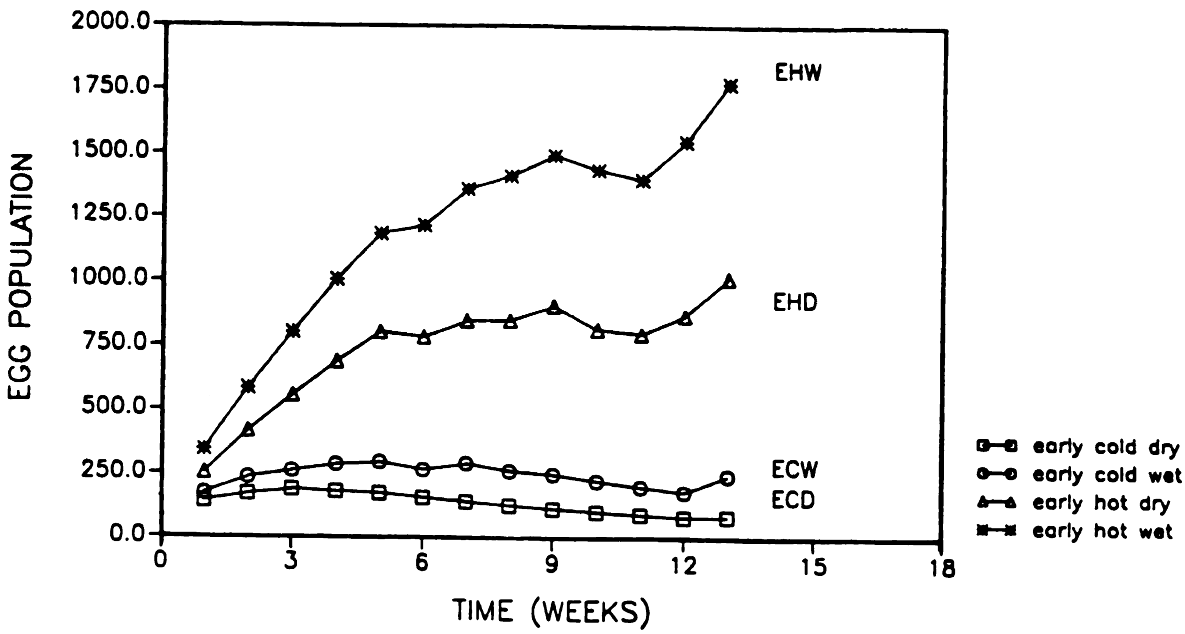

Fig 6.7 Egg population change with time under different conditions; storage began on May 1

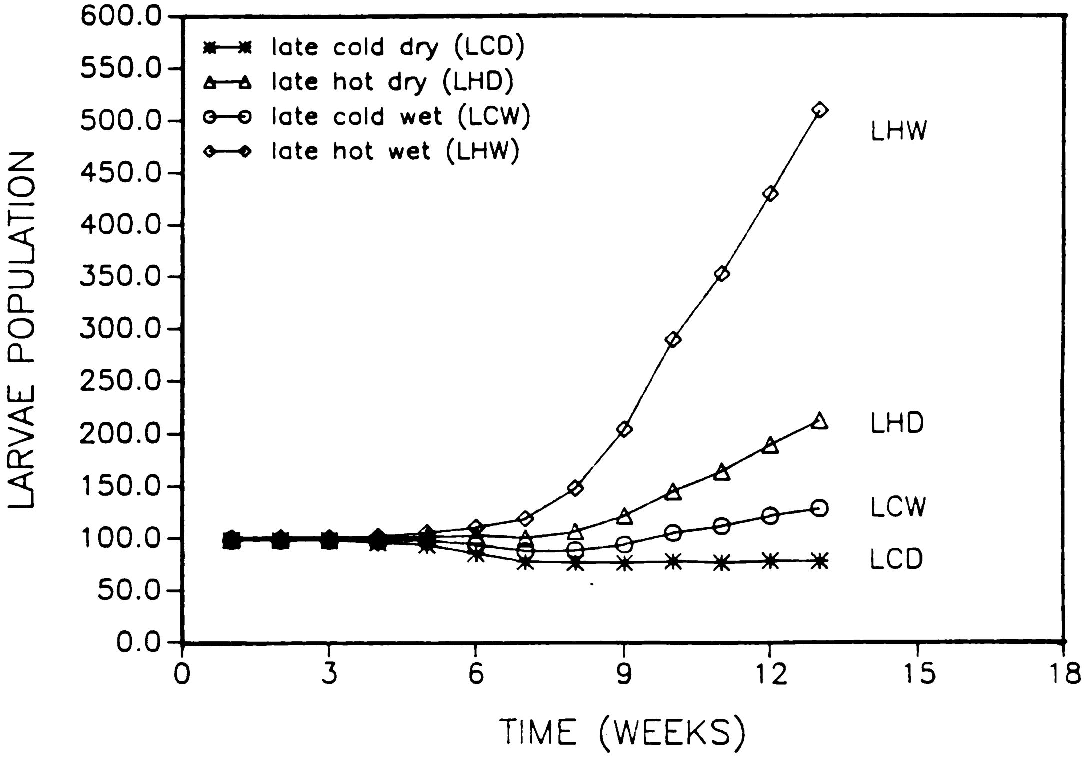

Fig 6.8 Fourth larval instar population change with time under different conditions; storage began on August 1

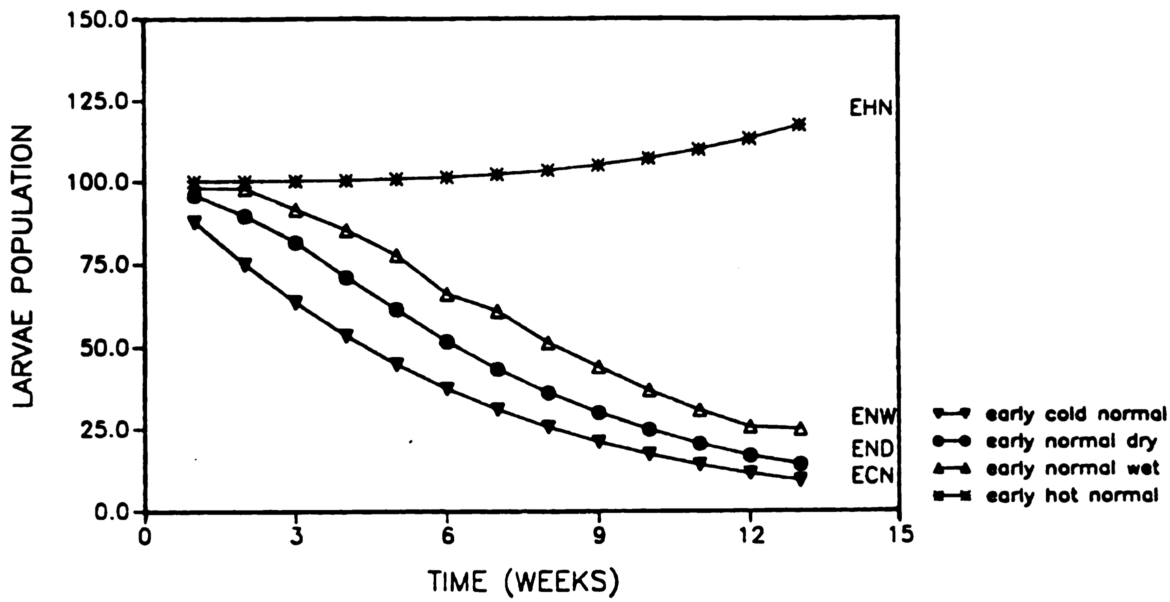

Fig 6.9 Fourth larval instar population change with time under different conditions; storage began on May 1

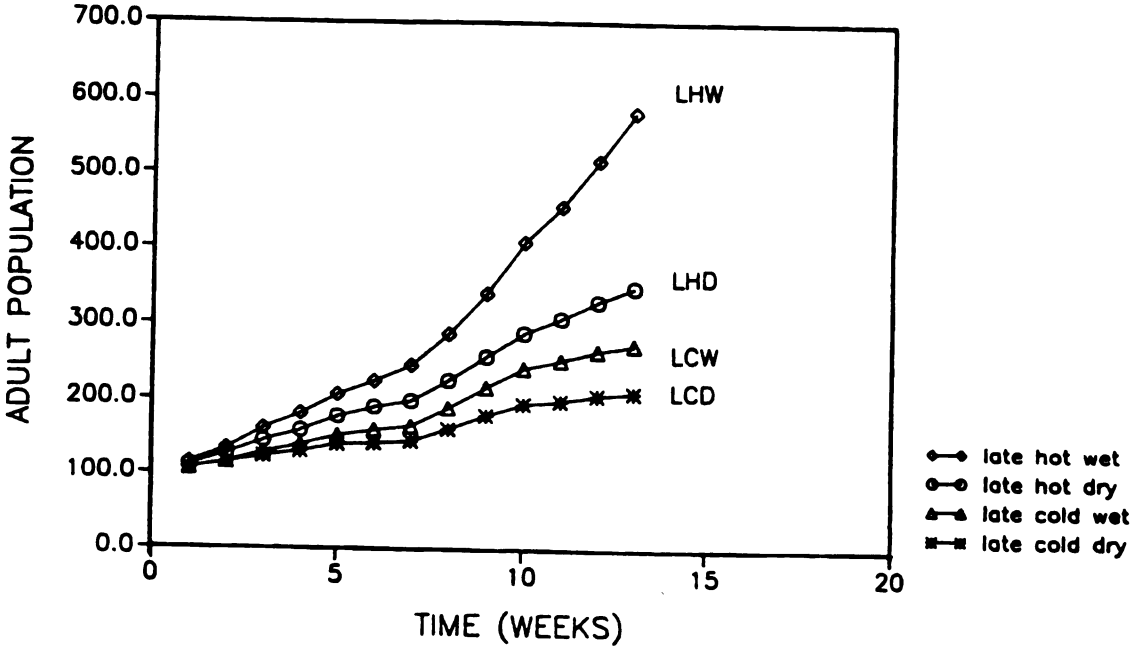

Fig 6.10 Adult weevil population change with time under different conditions; storage began on August 1

at 13% moisture content in a warmer than normal year.

In conclusion, the simulation of insect growth under Zimbabwe conditions has shown that the weather has an effect on; the predicted insect infestation and the magnitude of the stored insect populations is dependent on the initial moisture content of the grain and the time the grain is harvested and stored. Low temperature and grain moisture content limit infestations. Early storage (in Winter) ensures low incidence of infestations.

6.1.2 Maize weevil population growth in Michigan

The insect and drying/cooling models (i.e the system model) are used to simulate grain chilling under the temperature and relative humidity conditions encountered at the Jorgensen farm. Table 6.3 shows the grain temperatures during the first 192 hours of storage.

The insect infestation model is tested using varying inlet temperature and relative humidity values. The average inlet air conditions used in the simulation are (see Table 6.3):

- chilled air temperature 5.3^{o}C (dry bulb) and 3.9^{o}C (wet bulb)
- equilibrium relative humidity (Chung Pfost equation) in the grain interstices 80%.

An assumed infestation level is used as an input into the model to evaluate the effectiveness of chilling to control the maize weevil infestation.

The grain temperatures are below 10^{o}C and the moisture

Table 6.3 Simulated maize weevil population (individual insects) change with time in 18% corn stored at 10°C in Williamston, MI; under chilled conditions.

Stage	Initial population	Population after six days
Eggs	1000	941
Instar 1	1000	809
Instar 2	1000	848
Instar 3	1000	882
Instar 4	1000	917
Pupae	1000	999
Adults	1000	999

contents at about 18% (w.b). Therefore, the temperatures are too low for weevil development which results in a uniform reduction of the population in all the layers (see tables 4.2 and 4.3 for the temperature and relative humidity coefficients used in equation 39). If the grain is maintained in the same conditions, the insects will die in about twenty six weeks (Desmarchelier, 1988).

6.2 BIN COOLDOWN

6.2.1 Experimental

The test bin was filled in 25 hours. Cooling began when the grain was about 1m high at the bin wall. The cooling zone passed through the grain in about 168 hours (see Table 6.4).

Table 6.4 Experimental grain temperatures, and inlet air conditions, during the bin cooldown period of 18% moisture content corn stored in Williamston, MI; the bin was filled during the first 25 hours.

Time (hr)	Thermocouple levels * 1	2	3	4	5	6	Ta_{in}	T_{amb}	RH_{in}	Abs. Humidity
30	4.7	7.0	11.0	10.9	8.5	4.7	5.4	1.8	67.0	.004
36	4.4	6.7	10.1	11.2	10.1	3.3	4.0	0.2	74.0	.004
42	3.2	5.9	8.7	10.8	10.4	6.1	4.3	0.5	77.0	.004
48	3.2	5.5	8.3	10.8	11.1	6.8	5.2	13.4	87.0	.005
54	4.8	5.4	7.2	11.2	12.4	8.1	5.3	10.8	89.0	.005
60	6.0	4.8	6.4	10.7	12.1	9.8	5.6	10.6	90.0	.005
66	6.6	4.5	6.1	10.3	12.0	10.8	6.0	13.4	88.0	.005
72	7.0	4.4	5.8	9.8	11.9	11.2	5.3	17.8	84.0	.005
78	7.3	4.5	5.4	9.1	11.8	11.6	5.1	12.8	84.0	.005
84	7.4	4.6	5.1	8.4	11.6	12.0	4.9	11.5	85.0	.005
90	7.2	4.9	4.8	7.9	11.3	12.1	5.5	12.1	86.0	.005
96	7.2	4.9	4.8	7.9	11.2	12.0	5.5	9.5	86.0	.005
102	6.9	5.1	4.9	7.3	10.8	11.9	5.5	5.0	89.0	.005
108	6.4	6.1	4.2	6.4	9.8	11.2	4.6	3.8	91.0	.005
114	5.4	5.8	4.7	5.6	8.8	11.1	5.9	2.2	77.0	.004
120	4.4	5.8	4.3	4.9	8.0	10.8	6.8	0.7	69.0	.004
126	3.9	5.6	6.1	4.7	7.2	10.2	6.8	0.4	67.0	.004
132	3.6	5.2	6.6	4.2	6.5	9.6	6.2.	0.3	76.0	.004
138	4.2	4.7	6.7	4.3	5.9	8.8	6.2	0.4	80.0	.005
144	4.6	4.2	6.4	4.4	5.4	8.1	6.5	1.7	97.0	.006
150	5.5	4.0	5.9	4.6	4.9	7.6	4.6	4.2	96.0	.005
156	5.3	4.0	5.2	5.0	4.7	6.8	4.9	-	87.0	.005
162	5.5	4.5	4.7	5.5	4.9	6.4	4.5	-	93.0	.005
168	6.0	5.0	4.5	5.8	5.2	6.1	4.9	-	86.0	.005
174	6.0	5.2	4.4	6.0	5.4	5.8	3.3	-	97.0	.005
180	6.0	5.2	4.4	6.0	5.4	5.8	3.9	-	82.0	.004
186	6.0	5.2	4.4	6.0	5.4	5.8	4.7	-	71.0	.004
192	6.0	5.2	4.4	6.0	5.4	5.8	5.3	-	89.0	.005
Average							5.3		84.0	.005

* See Figure 5.1 for location of thermocouples

Ta_{in} = bin inlet air temperature
T_{amb} = ambient air temperature
airflow = 0.016 $m^3/m^2/s$; static pressure 1665Pa.

The initial grain temperature and moisture content were $10^{o}C$ + or - $2^{o}C$ and 18% + or - 1.5% (w.b), respectively. The inlet air relative humidity varied from 67 to 97%; with an average of 84%.

The ambient temperature fluctuated considerably (varied between 0.3 and $17.8^{o}C$) (see figure 6.11) but the controlled temperature of the chilled air blown into the bin ranged from 2.2 to $9.0^{o}C$. The hygrotherm (heater used to reduce air relative humidity) controlled the inlet relative humidity to the bin to between 61 and 97% (see Figure 6.11). The major deviation from the set point occurred when there was a large change in the ambient relative humidity and when there was a power failure.

The change in grain temperature at the 6 levels (see Figure 5.1) is illustrated in table 6.4 and figure 6.13. Figure 6.13 also illustrates how the temperature changed at the six levels which were monitored. The inlet air temperature ranged from 2.2 to 8.0 ^{o}C as the ambient temperature varied. The change in the inlet air temperatures is reflected in the grain temperature fluctuation during the bin cooldown (see figure 6.13). After 100 hours of cooling the temperatures decreased continuously until they stabilized at about $6^{o}C$.

Grain samples taken after the first cooldown cycle were at approximately 18% except for the peak of the pile where condensation was observed two weeks after storage, resulting in an increase of the grain moisture content to 20 - 22% (w.b).

6.2.2 Simulated

The chilling unit reduced the fluctuation of the ambient air

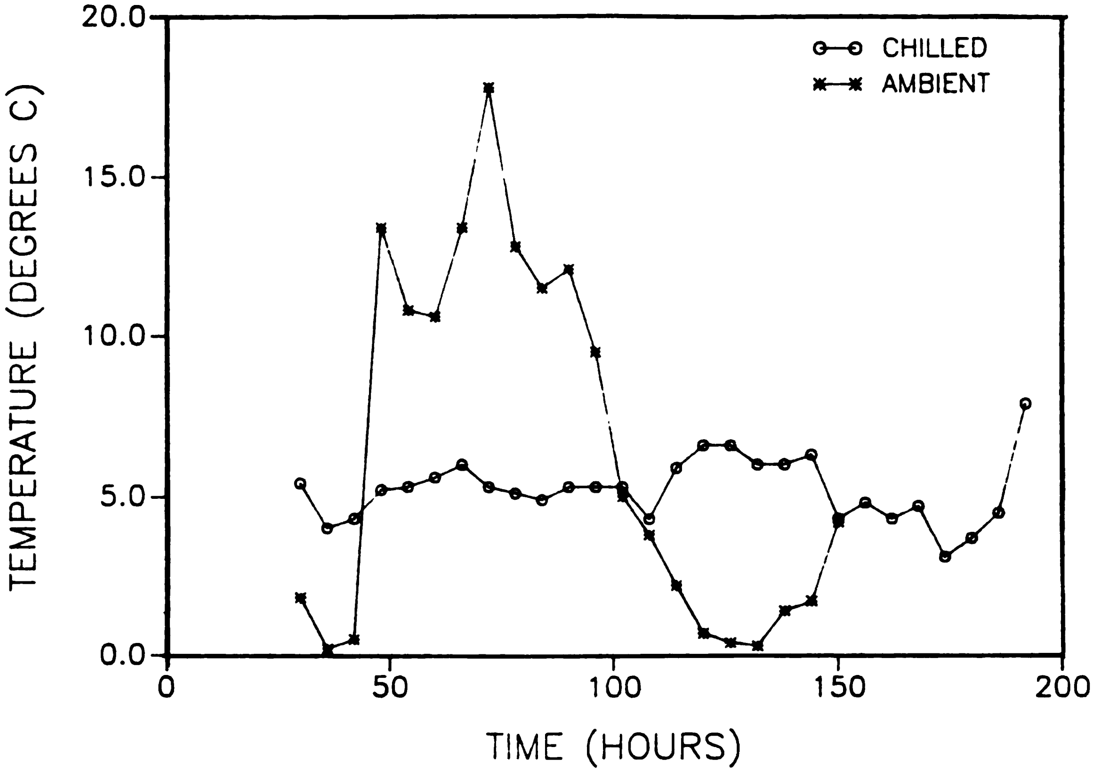

Fig 6.11 Variation of ambient and chilled inlet air temperatures with time.

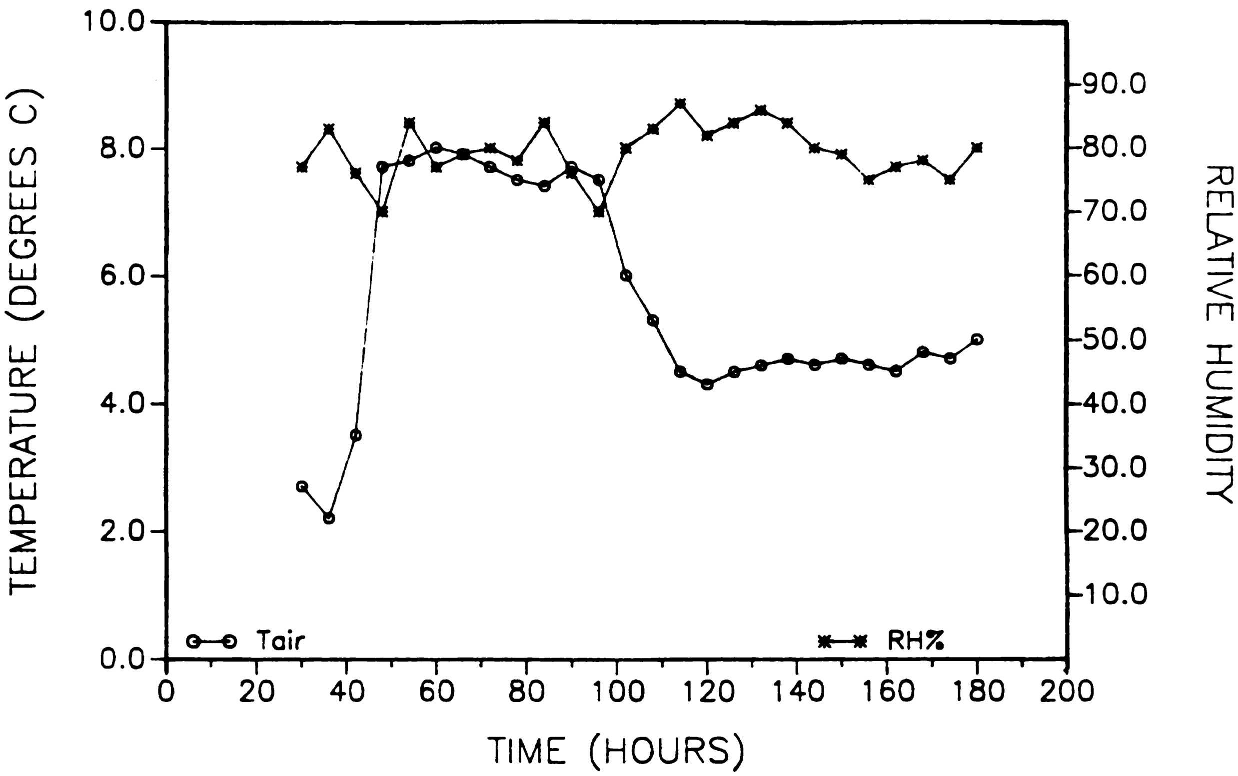

Fig 6.12 Variation of chilled air (Tair) temperatures and relative humidity (RH%) with time.

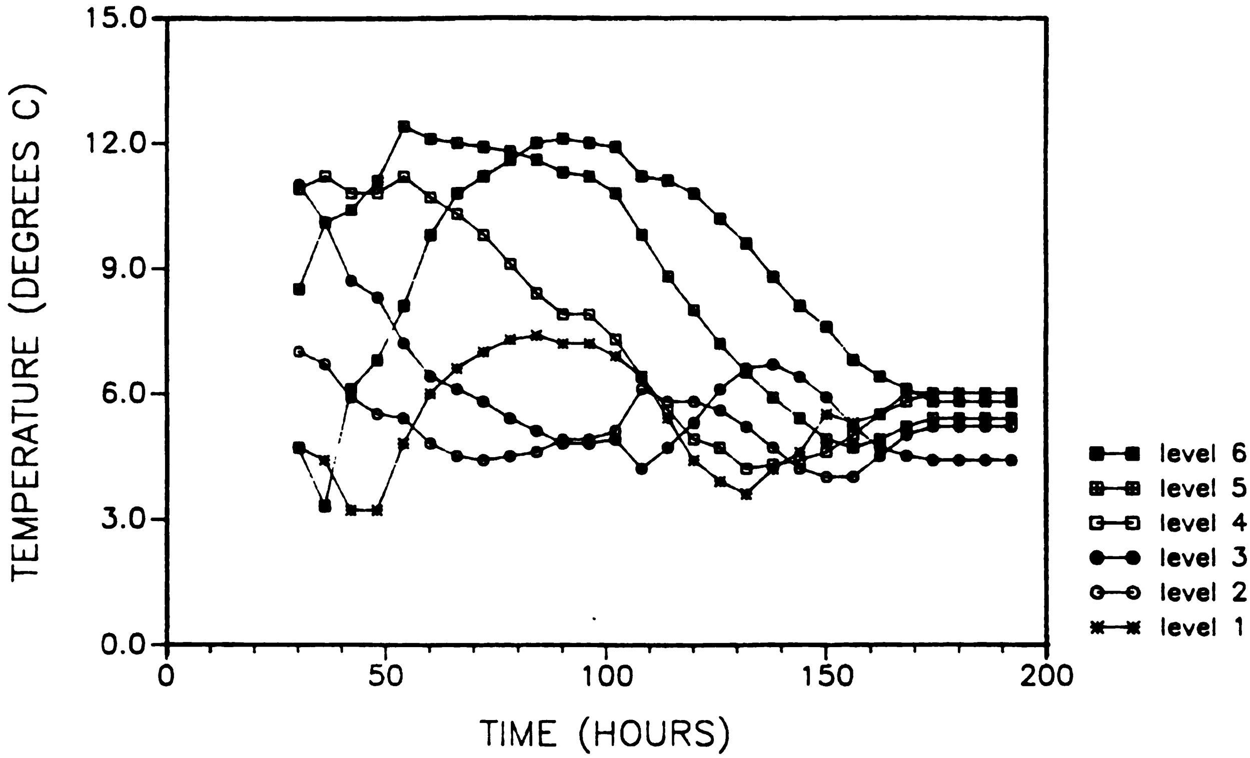

Fig 6.13 Grain temperature recorded by thermocouples on three cables at 6 levels: 1 to 6; 1 is the lowest level.

temperature and relative humidity. A temperature profile of the bin was used as an input at the beginning of the simulation. The temperatures used in the simulation were modified to reflect the increase in inlet temperature caused by the heat gain through the inlet hose.

The change in grain temperature at the six levels is also illustrated in table 6.5 and and Figure 6.14. The cooling zone passed through the grain in 140 hours. The temperatures in levels 1 and 2 fall below 6^{o}C in less than 110 hours.

6.2.3 Comparison of the experimental/simulated results

The difference between the experimental and simulated data is that the simulated temperatures remain slightly higher in the upper layers (see figure 6.15). This might be because of the fluctuation in the cooling air parameters in the experiment. This fluctuation in the ambient temperature and the temperature profile in the bin cannot be simulated precisely.

The results of the experimental bin cooldown reveal a variation in the air distribution as the cooling zone moves through the thermocouple layers. This fluctuation is due to the non uniformity of the grain in the bin. The temperatures in the experimental and simulated tests both stabilized after 168 hours to between 4 and 6^{o}C.

Although the results of the simulation and the experiment do not exactly match, the results are sufficiently close to justify using the model as a tool in the simulation of bin cooling with

Table 6.5 Simulated grain temperatures during the cooldown of 18% moisture content corn stored in Williamston, MI; using the weather conditions in figure 6.12; the bin was filled in 25 hours.

Time (hr)	Temperature levels * 1	2	3	4	5	6
30	5.6	5.8	10.6	10.9	9.7	6.2
36	4.7	5.3	7.8	10.4	10.2	7.5
42	6.4	5.2	6.8	9.6	10.3	8.6
48	8.3	5.8	6.2	8.7	9.9	9.4
54	8.3	6.3	6.0	7.8	9.3	9.7
60	8.1	8.3	6.1	7.1	8.6	8.6
66	8.3	8.7	6.7	6.7	7.9	8.5
72	8.5	8.9	7.5	6.6	7.4	8.8
78	8.6	7.9	7.3	6.8	7.0	8.3
84	8.3	7.3	8.7	7.0	7.0	8.1
90	8.9	7.8	7.3	7.5	7.0	7.7
96	7.0	6.9	6.6	6.2	6.1	6.6
102	6.8	6.9	6.8	8.5	6.4	6.3
114	5.4	6.2	6.6	6.3	6.7	7.6
120	5.9	6.3	7.2	6.8	6.5	7.8
126	5.6	5.8	7.0	6.7	6.6	7.9
132	4.8	5.0	6.8	6.6	6.6	8.0
138	4.4	4.7	6.4	6.5	6.5	7.8
144	3.6	4.9	6.3	6.4	6.6	7.6
150	3.5	5.2	6.2	6.2	6.3	7.5
156	3.8	5.6	5.9	6.1	6.4	7.3
162	3.9	5.3	5.7	6.2	6.3	7.2
168	4.0	5.5	5.9	6.1	6.3	6.8
174	3.8	5.3	5.9	6.0	6.0	6.4
180	4.2	5.2	5.9	6.0	6.1	6.4

* see figure 5.1 for the location of thermocouples
airflow = 0.019 $m^3/m^2/s$; static pressure = 250 Pa.

chilled air.

Figure 6.15 shows the grain temperature during simulated and experimental bin cooling recorded at the third level. The experimental temperature falls slightly before rising to 6.7^{o}C after which it falls to less than 6^{o}C. The simulated temperature stabilizes at a slightly higher temperature.

Static pressure is not used as a direct input into the model. The fan power and mechanical efficiency can be varied to reduce or increase air velocity in a way similar to modeling an increased or decrease of fines.

6.3 DISCUSSION OF THE TWO SUB - MODELS AND THE SYSTEM MODEL

The maize weevil growth sub-model (see appendix F) effectively demonstrates the influence of moisture content and temperature on insect development. The high mortality in the winter months of June and July in Zimbabwe when temperatures fall below 5^{o}C can be exploited to disinfest the grain. The use of the model reveals the critical factors. The model was tested with low insect population densities; it does not include the effect of density on the population growth. This is not a serious disadvantage because for high initial infestations , pest control measures must be employed. The AERATE/grain chilling model is limited to low airflow rates in order not to violate the assumptions made in the development of the model. The model provides an acceptable estimate of the general shapes of the grain temperature curves (see figures 6.14 and 6.15)

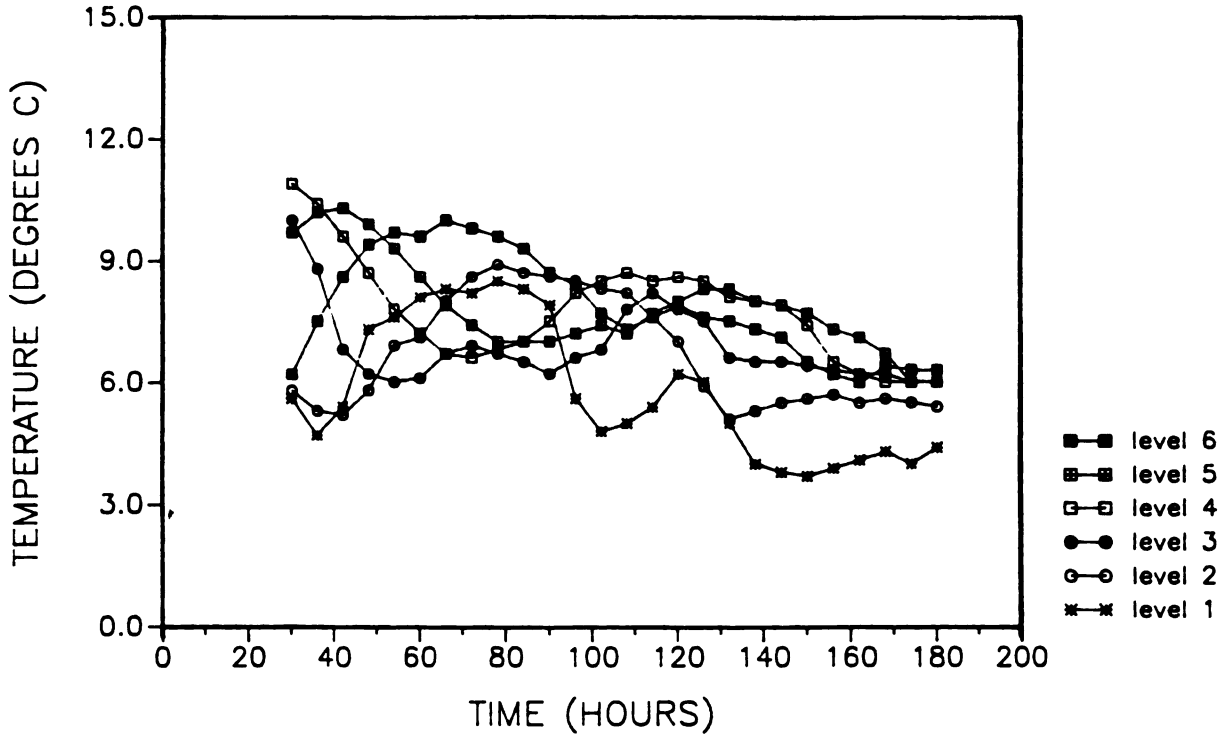

Fig 6.14 Grain temperature during simulated bin chilling recorded at 6 levels in a bin: 1 is the lowest level.

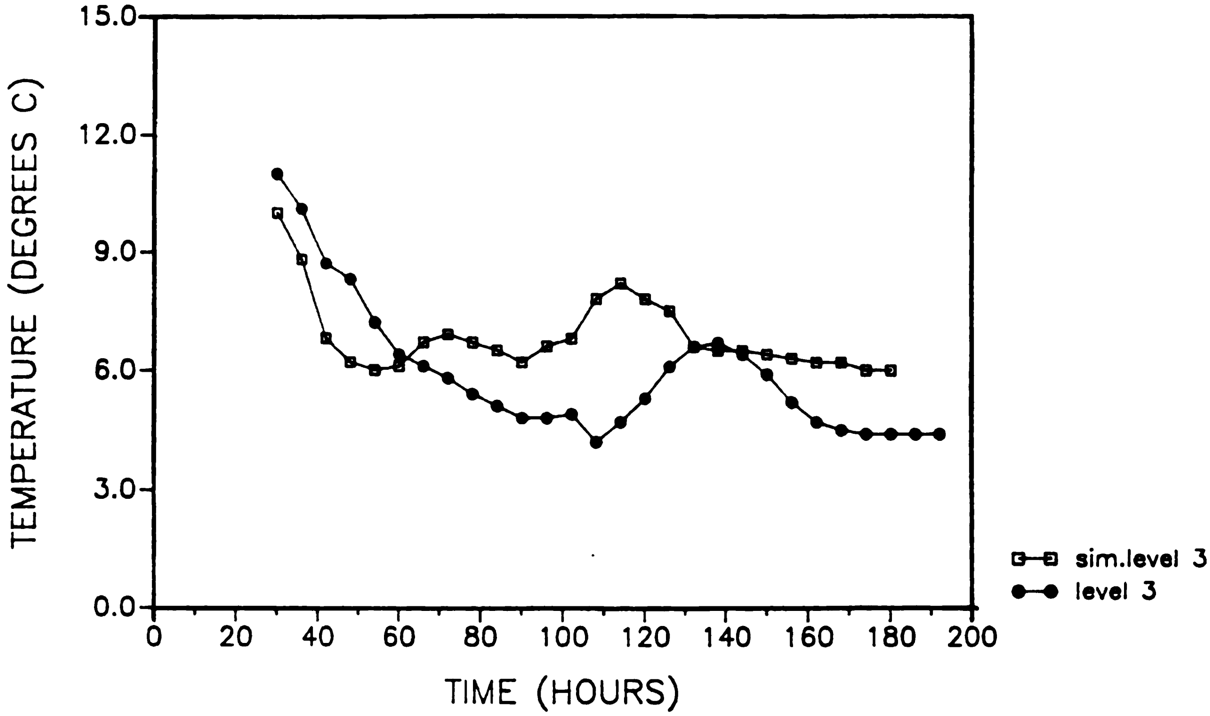

Fig 6.15 Comparison of grain temperature during simulated and experimental bin chilling recorded at level 3.

The combination of the two models, the system model, provides useful information on how effectively grain chilling controls the insect population growth. The size of equipment to be used and the operational details are calculated. The time taken to reach the desired grain temperature or the insect population level can be estimated.

The system model also provides information on weevil population growth under simulated continuous aeration using ambient air (see appendix E.9).

Grain chilling allows grain storage at higher moisture content. Dryer capacity is considerably increased by drying from 24% to 18% when compared to drying toless than 15%. The increase in dryer capacity is estimated as 50% at the Jorgensen farm.

CHAPTER VII

CONCLUSIONS

The first four objectives of the thesis have been achieved; the fifth objective has partially been achieved.

The available aeration and insect-population growth models have been analysed. They have several limitations because the input conditions are usually rigid and area specific. The two models that were selected are acceptable within these limits.

The combination of two physical/biological models was realized. The system model is flexible and utilizes weather data for continuous aeration.

Micro-climatic modification has a serious effect on insect infestation. The initial grain conditions are important. Farmers in Zimbabwe must harvest grain early to avoid field infestation. The grain temperature must be kept below 12°C if the moisture content is above 11% to minimize infestation.

Entomologists and engineers need to cooperate in developing simulation models that can aid in reducing losses to stored-grain pests.

CHAPTER VIII

SUGGESTIONS FOR FUTURE RESEARCH

This thesis has attempted to collect the relevant material on insect-population and grain-chilling models. There are many unknowns in both areas. The following recommendations are made:

1. More quantitative information is required on (a) the field infestation by maize weevils, (b) the effect of density on the rate of population growth, and (c) the rate of grain consumption by maize weevils.

2. The effectiveness of grain chilling appears good in the temperate areas where ambient temperatures are lowered soon after the fall harvest. Research on the appropriateness of grain chilling in the tropics is vital.

3. A comparison of the experimental and simulated data on chilled grain must be carried out over a long period in order to validate the models and improve the grain storage system model.

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LIST OF APPENDICES

APPENDIX A

GRAIN STORAGE STATISTICS FROM THE THE GRAIN MARKETING BOARD OF ZIMBABWE (G.M.B) FINANCIAL RECORDS. (GMB Records and Accounts, 1987).

A.1 Total annual quantities of selected grains handled by the G.M.B ('000 metric tonnes).

Crop	1986/87	1984/85	1983/84
Maize	3020	1334	1652
Wheat	407	280	307
Sorghum	126	125	23
Pearl Millet	71	4	-
Finger Millet	22	.4	-
Soybeans	84	-	-
Sunflowers	20	-	-
Groundnuts	16	-	-

A.2 Annual grain losses in storage (metric tonnes).

Crop	1986/87	1984/85	1983/84
Maize	6212	12000	4000
Wheat	6909	-	3000
Sorghum	369	-	340
Pearl Millet	157	-	16
Finger Millet	62	-	-
Soybeans	914	-	-
Sunflowers	261	-	-
Groundnuts	9	-	-

A.3 Producer grain price changes (Z$/metric ton).

Crop	1987/88	1986/87	1985/86	1984/85	1983/84
Maize	180	180	180	140	120
Wheat	300	299	283	250	220
Sorghum	172	172	173	134	120
Pearl Millet	250	250	240	250	-
Finger Millet	300	286	290	450	-
Soybeans	-	336	319	286	256
Sunflowers	-	332	315	277	-
Groundnut (kernels)		819	518	507	452

A.4 Annual Fumigation Costs (including non fumigants) (Z$ x 10E6).

	Chemicals	Total *
1987/88	1.22	-
1986/87	-	1.81
1985/86	-	1.56
1984/85	-	0.50

* The total excludes transport and subsistence allowances for the fumigation teams.

(GMB Records and Accounts, 1987).

APPENDIX B

THE ROLFES TEMPERATURE DETECTION SYSTEM.

The system that is used on the Jorgensen Farms has three cables arranged in a triangle (see Figures 5.1A and B). Each cable has 6 thermocouples made of copper and constantan.The thermocouples are located on the cable as follows:

Thermocouple number	Height from bin floor (m)
1	0.46
2	2.29
3	4.11
4	5.94
5	7.77
6	9.60

The sensing points are positioned near the outside of the cable so that heat is transmitted easily through the cable jacket. The manufacturer of the cables claims that the cables can give an indication of temperature of the grain within a radius of 3 to 3.7m.

APPENDIX C

TECHNICAL DATA FOR THE GRANIFRIGOR KK140 GRAIN CHILLING UNIT.

Power supply data:

Voltage and current type	460 V	3-phase
Power input max. efficiency*	17.1	kW
Operational current input max.	38	A
Max. starting current (direct-on-line-starting)	94	A
Recommended plug connection	63	A
Compressor:		
motor power max.	10.8	kW
refrigerating capacity		
at +30 C / +0 C	31.3	kW
at +40 C / +0 C	27.7	kW
Chilled air fan:		
motor power	5.5	kW
speed	2900	rpm
motor protection	IP 54/55	
motor pattern	B5	
Condenser fan:		
motor power	0.55	kW
speed	960	rpm
motor protection	IP 54	
Max. admissable operating overpressure (pressure limiter trips at 25 bar)	25 bar	
Max. condensing temperature	63	^{o}C
R 22 refrigerant filling	23	kg
Refrigerating machine oil	3.65	litres
Noise level at 7 m distance	68.5 dB	

* Under nominal operating conditions 3500 m^3/h

SULZER ESCHER WYSS GMBH, Postfach 1380, D-8990 Lindau/Bodensee.

APPENDIX D

SYSTEM MODEL OPERATION

AERATE includes the maize weevil population growth model as a subroutine. The aeration simulation is based on actual weather data. The weather files are on the same directory of the disk as the main program.

In order to start the program on a computer with a co-processor, type the following command at the DOS-prompt:

A> AERATE <RETURN-key>

The simulation program requires 512K memory and disk space. In order to accomodate lengthy output files, it is preferable to run the program on a hard drive or high-density floppy drive. The output files can be saved on a second-disk drive by specifying the drive name in front of the name.

4.1 Required input data

After choosing the input and output files, as well as the aeration operation desired, the program program prompts the operator to provide the inputs. The program has built-in psychometric subroutines which calculate air parameters using the hourly temperature and relative humidity and barometric pressure.

In the chilling operation, it is assumed that inlet air temperature and relative humidity are supplied by a grain cooling unit independent of the ambient conditions. The cooling air temperature and relative humidity remain as entered by the user, i.e the air inlet conditions are constant and the fan does not heat the air.

APPENDIX E

MAIZE WEEVIL POPULATION GROWTH OVER TIME UNDER DIFFERENT CONDITIONS: E1 to E9.

E.1

End of Week	Eggs	Larval instars 1	2	3	4	Pupa	Adults
1	342.0	128.0	102.0	100.0	100.0	106.0	132.0
2	582.0	211.0	124.0	104.0	100.0	111.0	165.0
3	800.0	316.0	165.0	115.0	103.0	114.0	194.0
4	1003.0	432.0	223.0	137.0	109.0	118.0	221.0
5	1181.0	542.0	287.0	165.0	119.0	122.0	245.0
6	1215.0	547.0	298.0	172.0	121.0	124.0	252.0
7	1358.0	644.0	356.0	202.0	133.0	129.0	271.0
8	1410.0	668.0	377.0	215.0	139.0	133.0	279.0
9	1493.0	713.0	411.0	237.0	150.0	138.0	292.0
10	1437.0	632.0	378.0	226.0	146.0	141.0	289.0
11	1399.0	582.0	348.0	216.0	143.0	143.0	288.0
12	1549.0	694.0	401.0	244.0	159.0	149.0	309.0
13	1775.0	861.0	497.0	296.0	187.0	163.0	341.0

Conditions:
a) moisture content 13%
b) threshold 12.6°C
c) temperature factor 1.15
d) storage began on May 1

E.2

End of Week	Eggs	Larval instars 1	2	3	4	Pupa	Adults
1	215.0	109.0	100.0	100.0	100.0	104.0	120.0
2	415.0	148.0	106.0	100.0	100.0	108.0	142.0
3	554.0	199.0	120.0	103.0	100.0	110.0	161.0
4	685.0	258.0	141.0	108.0	101.0	112.0	179.0
5	800.0	316.0	165.0	115.0	103.0	114.0	194.0
6	781.0	291.0	155.0	107.0	95.0	114.0	194.0
7	845.0	321.0	166.0	109.0	94.0	114.0	203.0
8	846.0	312.0	163.0	105.0	90.0	113.0	205.0
9	902.0	341.0	175.0	110.0	90.0	113.0	212.0
10	812.0	276.0	146.0	94.0	79.0	110.0	203.0
11	796.0	264.0	137.0	88.0	74.0	108.0	202.0
12	869.0	306.0	152.0	94.0	76.0	106.0	211.0
13	1012.0	395.0	190.0	108.0	80.0	105.0	227.0

Conditions:
a) moisture content 11%
b) threshold 12.6°C
c) temperature factor 1.15
d) storage began on May 1

E.3

End of Week	Eggs	Larval instars 1	2	3	4	Pupa	Adults
1	171.0	100.0	99.0	99.0	99.0	100.0	109.0
2	233.0	107.0	100.0	100.0	99.0	103.0	117.0
3	259.0	101.0	89.0	90.0	93.0	104.0	122.0
4	284.0	99.0	80.0	82.0	87.0	104.0	126.0
5	293.0	94.0	70.0	72.0	79.0	103.0	128.0
6	264.0	79.0	55.0	58.0	67.0	100.0	126.0
7	289.0	82.0	51.0	53.0	62.0	98.0	129.0
8	260.0	71.0	41.0	42.0	52.0	94.0	126.0
9	247.0	66.0	35.0	35.0	45.0	90.0	124.0
10	222.0	58.0	29.0	28.0	38.0	85.0	121.0
11	200.0	51.0	25.0	23.0	31.0	80.0	118.0
12	180.0	46.0	21.0	18.0	26.0	75.0	114.0
13	244.0	58.0	24.0	19.0	25.0	71.0	120.0

Conditions:
a) moisture content 13%
b) threshold 12.6°C
c) temperature factor 0.85
d) storage began on May 1

E.4

End of Week	Eggs	Larval instars 1	2	3	4	Pupa	Adults
1	140.0	90.0	92.0	93.0	95.0	101.0	105.0
2	169.0	81.0	85.0	81.0	89.0	101.0	110.0
3	186.0	73.0	69.0	74.0	81.0	101.0	113.0
4	178.0	61.0	54.0	61.0	70.0	99.0	113.0
5	171.0	53.0	43.0	50.0	61.0	96.0	113.0
6	154.0	45.0	33.0	39.0	51.0	92.0	111.0
7	139.0	39.0	26.0	31.0	43.0	88.0	109.0
8	125.0	34.0	21.0	25.0	36.0	83.0	107.0
9	112.0	29.0	17.0	19.0	30.0	78.0	104.0
10	101.0	26.0	14.0	15.0	24.0	73.0	102.0
11	91.0	23.0	11.0	12.0	20.0	68.0	99.0
12	82.0	21.0	9.0	10.0	16.0	63.0	96.0
13	83.0	19.0	8.0	8.0	14.0	58.0	94.0

Conditions: a) moisture content 11%
b) threshold 12.6°C
c) temperature factor 0.85
d) storage began on May 1

E.5

End of Week	Eggs	Larval instars 1	2	3	4	Pupa	Adults
1	142.0	94.0	95.0	96.0	97.0	101.0	105.0
2	205.0	99.0	95.0	96.0	97.0	102.0	114.0
3	268.0	108.0	96.0	96.0	97.0	104.0	122.0
4	318.0	116.0	94.0	93.0	95.0	105.0	129.0
5	385.0	132.0	94.0	91.0	93.0	106.0	139.0
6	390.0	126.0	84.0	80.0	85.0	105.0	140.0
7	403.0	125.0	76.0	71.0	77.0	104.0	143.0
8	535.0	174.0	90.0	74.0	76.0	102.0	160.0
9	686.0	245.0	116.0	80.0	76.0	101.0	178.0
10	817.0	316.0	148.0	90.0	78.0	100.0	194.0
11	848.0	326.0	156.0	92.0	76.0	99.0	198.0
12	913.0	366.0	176.0	99.0	78.0	99.0	206.0
13	941.0	376.0	185.0	103.0	78.0	98.0	209.0

Conditions:
a) moisture content 11%
b) threshold 12.6°C
c) temperature factor 0.85
d) storage began on August 1

E.6

End of Week	Eggs	Larval instars 1	2	3	4	Pupa	Adults
1	180.0	101.0	99.0	99.0	99.0	102.0	110.0
2	296.0	117.0	101.0	100.0	100.0	105.0	126.0
3	424.0	151.0	107.0	100.0	100.0	108.0	143.0
4	526.0	188.0	117.0	102.0	100.0	110.0	157.0
5	666.0	249.0	137.0	107.0	101.0	112.0	176.0
6	761.0	296.0	156.0	113.0	102.0	114.0	189.0
7	814.0	316.0	166.0	113.0	103.0	114.0	197.0
8	1020.0	435.0	224.0	135.0	106.0	117.0	224.0
9	1259.0	588.0	313.0	176.0	121.0	123.0	256.0
10	1483.0	740.0	415.0	230.0	145.0	132.0	287.0
11	1619.0	835.0	482.0	270.0	164.0	141.0	306.0
12	1769.0	940.0	561.0	319.0	189.0	153.0	329.0
13	1896.0	994.0	613.0	358.0	212.0	167.0	347.0

Conditions: a) moisture content 11%
b) threshold 12.6^{o}
c) temperature factor 1.15
d) storage began on August 1.

E.7

End of Week	Eggs	Larval instars 1	2	3	4	Pupa	Adults
1	142.0	94.0	95.0	96.0	97.0	101.0	105.0
2	214.0	100.0	95.0	96.0	97.0	105.0	115.0
3	304.0	115.0	97.0	96.0	97.0	105.0	127.0
4	386.0	136.0	101.0	97.0	97.0	106.0	138.0
5	478.0	167.0	108.0	98.0	97.0	108.0	150.0
6	529.0	182.0	108.0	93.0	93.0	108.0	158.0
7	560.0	189.0	106.0	87.0	87.0	108.0	163.0
8	751.0	281.0	140.0	96.0	88.0	108.0	188.0
9	971.0	407.0	201.0	118.0	94.0	109.0	216.0
10	1172.0	536.0	276.0	151.0	105.0	112.0	241.0
11	1250.0	578.0	309.0	169.0	111.0	114.0	252.0
12	1347.0	646.0	352.0	192.0	121.0	118.0	264.0
13	1395.0	660.0	372.0	207.0	128.0	121.0	272.0

Conditions: a) moisture content 13%
b) threshold 12.6°
c) temperature factor 0.85
d) storage began on August 1.

E.8

End of Week	Eggs	Larval instars 1	2	3	4	Pupa	Adults
1	206.0	103.0	100.0	99.0	99.0	103.0	114.0
2	351.0	130.0	103.0	100.0	100.0	106.0	133.0
3	544.0	195.0	119.0	102.0	100.0	110.0	160.0
4	695.0	262.0	143.0	108.0	101.0	113.0	180.0
5	886.0	364.0	188.0	123.0	105.0	116.0	206.0
6	1023.0	444.0	229.0	140.0	110.0	118.0	224.0
7	1171.0	536.0	283.0	163.0	118.0	122.0	244.0
8	1475.0	738.0	416.0	233.0	148.0	135.0	286.0
9	1830.0	983.0	596.0	343.0	204.0	162.0	339.0
10	2227.0	1251.0	806.0	488.0	289.0	210.0	406.0
11	2488.0	1420.0	941.0	586.0	352.0	249.0	454.0
12	2801.0	1614.0	1094.0	701.0	429.0	300.0	515.0
13	3126.0	1806.0	1243.0	814.0	509.0	356.0	581.0

Conditions:
a) moisture content 11%
b) threshold 12.6°
c) temperature factor 1.15
d) storage began on August 1.

E.9 Variation of the grain temperature, moisture content and insect population ('0) in layer 2 of corn stored in Zimbabwe.

End of Week	M.C (% w.b)	Temp. ^{o}C	Eggs	Larval instars				Pupa	Adults
				1	2	3	4		
0	18.0	20.0	100	100	100	100	100	100	100
1	17.2	13.0	162	100	100	100	100	102	108
2	16.8	13.5	245	106	100	100	100	104	117
3	16.6	13.8	288	116	101	100	100	105	125
4	16.3	13.6	351	131	103	100	100	107	134
5	15.9	11.7	415	149	107	101	100	108	143
6	15.6	11.4	480	171	112	102	100	109	151
7	15.3	11.3	528	186	115	100	98	110	158
8	15.0	10.5	594	214	123	102	98	111	167
9	14.7	11.6	660	244	134	104	99	112	176
10	14.4	10.3	726	276	147	108	100	113	185
11	14.1	12.3	753	283	149	106	96	113	189
12	13.9	12.2	820	320	164	111	97	113	198
13	13.5	15.2	888	358	182	117	99	114	207
14	13.1	16.1	957	398	202	125	101	115	216
15	12.7	18.1	1025	439	224	133	104	116	225
16	12.3	18.6	1094	482	248	144	108	117	234
17	11.9	17.7	1163	527	274	156	112	118	243

Air velocity 0.019 m/s

APPENDIX F

The maize weevil population growth sub-model.

```
C ***********************************************************************
      SUBROUTINE WEEVIL(ZEITINT)
      COMMON/ARRAYS/XMWEEV(70),RWEEV(70),TWEEV(70),PEGG(70),
     +PLAR1(70),PLAR2(70),PLAR3(70),PLAR4(70),PPU(70),PAD(70)
      COMMON /POPO/PEGGO,PLAR1O,PLAR2O,PLAR3O,PLAR4O,PPUO,PADO,TONSO
      COMMON/VARI/THETA,CONS,XINFE,THRE
      COMMON/SILO/SZAHL,HGUT,SDICKE,ASILO,WSW,RADIUS,ASW
      DIMENSION RH(70),MC(70),RF(70),MF(70),KERNA(70),CONSA(70),XINFEA(7
     +0)
      REAL MC,MF,RH,RF,KERNA
      REAL KERN
      CONS=0.
      KERN=0.
      XINFE = 0.
      IOFT=INT(24./ZEITINT)
      ISZAHL=INT(SZAHL)
      DO 300 I=1,ISZAHL
        CONSA(I)=0.
        KERNA(I)=0.
        RH(I)=RWEEV(I)/FLOAT(IOFT)
        MC(I)=XMWEEV(I)/FLOAT(IOFT)
  300 CONTINUE
C     CALCULATION OF THE MOISTURE CONTENT COEFFICIENT
      DO 100 J=1,ISZAHL
      IF (MC(J).GE. 5..AND.MC(J).LT.10.)MF(J) = .4+.1*(MC(J)- 9.)
      IF (MC(J).GE.10..AND.MC(J).LT.11.)MF(J) = .5+.2*(MC(J)-10.)
      IF (MC(J).GE.11..AND.MC(J).LT.12.)MF(J) = .7+.3*(MC(J)-11.)
      IF (MC(J).GE.12..AND.MC(J).LT.13.)MF(J) = 1.
      IF (MC(J).GE.13..AND.MC(J).LT.14.)MF(J) = 1.-.1*(MC (J)-13.)
      IF (MC(J).GE.14..AND.MC(J).LT.15.)MF(J) = .3-.1*(MC (J)-14.)
      IF (MC(J).GE.15..AND.MC(J).LT.23.)MF(J) = .8-.1*(MC (J)-15.)
      IF (MC(J).LT. 5..OR.MC(J).GE.23.)MF(J) = 0.
C     CALCULATION OF THE RELATIVE HUMIDITY COEFFICIENT
      IF (RH(J).LT.45.) RF(J) = .5*RH(J)/45.
      IF (RH(J).GE.45..AND. RH(J).LT.55.) RF(J)=.5+.2*(RH(J)-45.)/10.
      IF (RH(J).GE.55..AND. RH(J).LT.65.) RF(J)=.7+.3*(RH(J)-55.)/10.
      IF (RH(J).GE.65..AND. RH(J).LT.75.) RF(J) = 1.
      IF (RH(J).GE.75..AND. RH(J).LT.85.) RF(J)=1.-.2*(RH(J)-75.)/10.
      IF (RH(J).GE.85.) RF(J) = .8 - .2 * (RH(J) - 85.)/15.
C     Save current population values:
      PLAR1C = PLAR1(J)
```

```
      PLAR2C = PLAR2(J)
      PLAR3C = PLAR3(J)
      PLAR4C = PLAR4(J)
      PPUC = PPU(J)
C     CALCULATION OF DEGREE HOURS USING TEMPERATURE(THETA) FROM THE
C     AERATION MODEL OR HOURLY TEMPERATURE
      TEMP=(TWEEV(J) - THRE*FLOAT(IOFT))/24.
      DEGD = (TEMP * MF(J) * RF (J) )
      IF( DEGD.LE.0.) DEGD  = 0.
      IF ( DEGD.EQ.0.)  GOTO 200
      IF (DEGD-FLOAT(INT(DEGD)).GE.0.5)DEGD=DEGD+0.5
      IDEGD=INT(DEGD)
C     CALCULATION OF THE POPULATION CHANGE   THE NUMBER OF COMPUTATIONS
C     IS EQUAL TO THE NUMBER OF DEGREE DAYS CALCULATED   THIS PART OF
C     THE PROGRAM IS USED ONLY WHEN THE VALUE OF DEGD IS>0
  210 PAD(J) = 1359.* PAD(J) / 1360. +PPU(J) / 80.
      PPU(J) = 79.* PPU(J)/80. + PLAR4(J) / 65.
      PLAR4(J) = 64.* PLAR4(J)/65. + PLAR3(J) /65.
      PLAR3(J) = 64.* PLAR3(J)/65. + PLAR2(J) /65.
      PLAR2(J) = 64.* PLAR2(J)/65. + PLAR1(J) /65.
      PLAR1(J) = 64.* PLAR1(J)/65. + PEGG(J) /80.
      PEGG(J)  = 79.* PEGG(J)/80. + .1*PAD(J)
      IDEGD=IDEGD-1
      IF (IDEGD.LE.0)GOTO 220
      GOTO 210
C     CALCULATION OF THE DECREASE IN POPULATION WHEN THE DEGREE DAYS
C     ARE EQUAL TO ZERO
  200 XMORAT = 0.95
      PAD(J) = 1.04 * XMORAT * 1359.* PAD(J)/1360. + PPU(J)/80.
      PPU(J)  = 1.05 * XMORAT * 79.* PPU(J)/80. + PLAR4(J)/65.
      PLAR4(J) = 1.03 * XMORAT * 64.* PLAR4(J)/65.+ PLAR3(J)/65.
      PLAR3(J) = 1.02 * XMORAT * 64.* PLAR3(J)/65.+ PLAR2(J)/65.
      PLAR2(J) = 1.01 * XMORAT * 64.* PLAR2(J)/65.+ PLAR1(J)/65.
      PLAR1(J) = XMORAT * 64.* PLAR1(J)/65. + PEGG(J)/80.
      PEGG(J) = 1.05 * XMORAT * 79.* PEGG(J)/80.
C     CALCULATION OF THE AMOUNT OF GRAIN CONSUMED PER DEGREE DAY
  220 CONSA(J)=CONSA(J)+((PLAR1(J)*0.35/260.)+(PLAR2(J)/260.)+(PLAR3(J)
     +*1.5/260.)+(PLAR4(J) * 4.5/260.)+(PAD(J)* 3.79/357)) *
     +0.000001
C     Calculate the population change in the layer:
      PLAR1C = PLAR1(J) -PLAR1O
      IF(PLAR1C.LT.0) PLAR1C = 0.
      PLAR2C = PLAR2(J) -PLAR2O
      IF(PLAR2C.LT.0) PLAR2C = 0.
      PLAR3C = PLAR3(J) -PLAR3O
      IF(PLAR3C.LT.0) PLAR3C = 0.
      PLAR4C = PLAR4(J) -PLAR4O
      IF(PLAR4C.LT.0) PLAR4C = 0.
      PPUC = PPU(J) -PPUO
      IF(PPUC.LT.0) PPUC = 0.
C     CALCULATION OF THE NUMBER OF KERNELS INFESTED
      KERNA(J)=KERNA(J)+PEGGO+PLAR1O+PLAR2O+PLAR3O+PLAR4O+PPUO+
```

```
     +.1*PAD(J)+PLAR1C+PLAR2C+PLAR3C+PLAR4C+PPUC
C     %INFESTATION, ASSUMING THAT THERE ARE 3800 KERNELS PER KG:
      XINFEA(J) = KERNA(J)/(38.0E3*TONSO/SZAHL)
  100 CONTINUE
      DO 305 I=1,ISZAHL
        CONS = CONS+CONSA(I)
        XINFE = XINFE+XINFEA(I)
  305 CONTINUE
      XINFE = XINFE/SZAHL
      RETURN
      END
```