CLIMATE AND THE INFESTATION OF STORED CEREALS BY INSECTS*

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ABSTRACT: Climate plays an important role in determining whether insect species of stored cereals and their products will become established as major pests in food-storing regions of the world. Using a recognized climatic classification of regions where major cereal crops are produced, the characteristic patterns of infestation of storage insects predominant in these regions are examined. Heterogeneity of species distribution and variation in insect density corresponding to diversity of climatic conditions within a region, such as the European USSR, Ghana, Uttar Pradesh in India, and Australia are emphasized. The climatic conditions during harvest in cereal producing regions are analyzed and considered an important factor in setting the pattern for post-harvest deterioration of stored grain. Laboratory data on physical limits and the intrinsic rate of increase of major storage insect species are integrated to develop a climatic plasticity index (Ip) for each species. According to this index *Tribolium castaneum* (Herbst), *Cryptolestes ferrugineus* (Stephens), and *Oryzaephilus surinamensis* (L.) are found to be among the most adaptable and *Trodogerma granarium* Everts and, *Corcyra cephalonica* (Stainton) among the less adaptable species. How the basic relationships between climatic variables and infestation records can be used to predict potential insect outbreaks is illustrated by a deductive multivariate analysis of 3 years' insect infestation data from 41 crop districts in the Canadian Prairies. Proposals for future research are outlined.

Climate sets the basic limits within which food plants can be grown, harvested, stored, and distributed. Plants and animal pests which infest foodstuffs must also operate within specific limits imposed on them by their genotype and climate. The causes and consequences of infestation of foodstuffs are complex; cereal grains and the organisms that attack them not only have their characteristic properties but also are affected by many physical, chemical, biotic and man-made variables. For example, a crop of Manitoba wheat may be harvested damp by a combine, infected by fungi and bacteria, dried by a drier, stored in a metal bin, and subsequently infested by insects, fumigated, transported by a truck, a railway box car and a ship and so on.

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Climate is defined as the mean physical conditions that have a major effect on the mean population density of a species. Weather is defined as day-to-day or seasonal conditions which usually include extremes, and has a major influence on the survival of organisms. For convenience in discussion, weather is considered as a component of climate in this paper. Climate changes the quality of stored cereals directly by acting on seed properties, such as by disrupting the enzyme mechanism of the dormant seed, and indirectly by influencing harvest and storage conditions, and the rate of increase of various biotic agents which invade stored grain (Fig. 1).

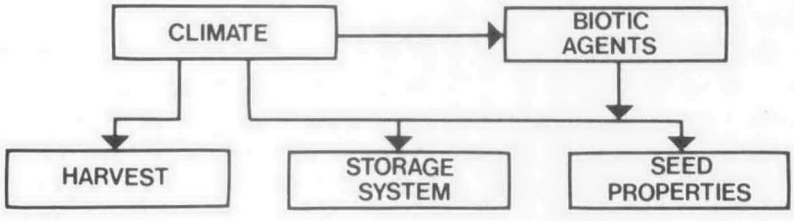

FIGURE 1. A schema illustrating general influence of climate on cereal harvest, storage system, seed properties and biotic agents infesting stored cereals.

Because we are primarily interested in the role of insects in effecting change, a schema of direct effects of climate, insect genotype and nutrition on an insect population that lead to outbreaks, spoilage of stored cereals and economic loss is presented in Fig. 2. Indirect effects of climate on insect populations through endocrine systems, parasites, predators [1], microflora, and man-made structural and other types of barriers are shown in Fig. 3. The weather component of climate affects insects by acting on the endocrine system that regulates diapause formation and influences survival, development and reproduction; it also affects the individuals of a species as a density-independent catastrophic factor. Because many stored-product insects live in a relatively protected environment provided by a mass of food stuffs around them and only a few species have diapause, the weather effect is often not conspicuous. Diurnal, seasonal and annual changes in temperature and relative humidity, particularly where such changes are pronounced, often critically determine the population size of a stored-product species. In a stored-grain environment insect performance can also be affected by the growth of fungi and bacteria, parasites and predators which in turn are influenced, if not regulated by climate. In addition, the genotype of a species and the nutrition provided by the stored seeds also influence the 3 basic physiological processes of the insect. If an insect species can exploit the climatic and other conditions of its niche to its advantage, it will succeed and multiply into explosive outbreak numbers. At this stage human action, the weather component

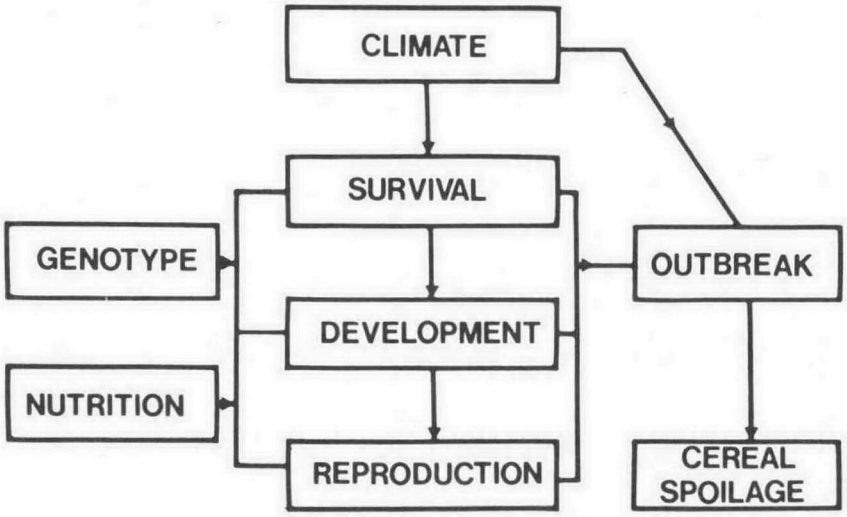

FIGURE 2. A schema of the main effects of climate, genotype and nutrition on a stored-product insect population that lead to an outbreak, cereal spoilage and economic loss. Climate also includes weather effect.

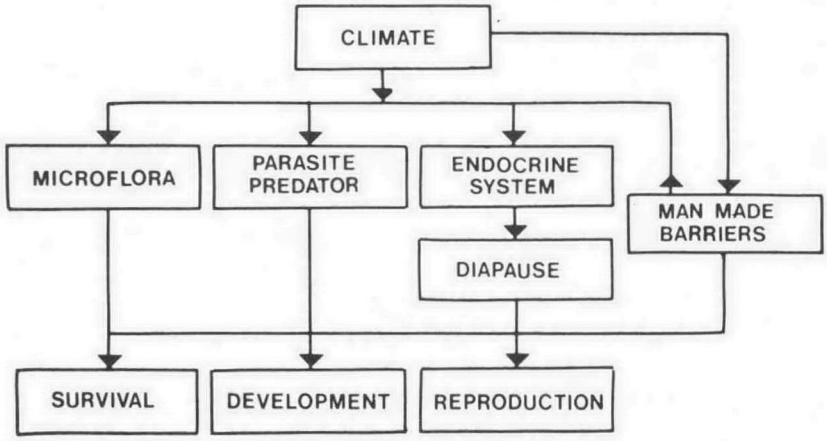

FIGURE 3. A schema of indirect effect of climate on insect population through its own endocrine system, parasites and predators, seed-borne microflora, and man-made structural and other types of barriers.

of climate, or both may prevent the insect colony from flourishing further. If control measures are applied, insects cease to thrive and the stored grain is salvaged for human or animal use. If no control measure is applied cereals are totally spoiled causing eventual death of the insects by starvation, lack of protection from the weather extremes, and by production of toxic substances from their own bodies and from microbial species.

To explain clearly the climatic effect on insect infestation and spoilage of stored cereals, only environments, cereal

types and insect species of certain categories are considered in this paper. The categories are as follows:

Environmental protection

The niches of stored-grain insects are broadly divided into 2 groups of environments:

(i) Unprotected - Minimum protection from climate although temporary insulation is provided by the structure and the cereal substrate; e.g. insects in empty and small granaries, in bags, metal, earthen containers in unheated or non-air-conditioned premises.

(ii) Protected environment - Adequate protection from external climatic and weather effect; e.g. large grain bulks, well constructed large elevators and silos; heated, refrigerated or air-conditioned granaries, warehouses, flour and feed mills.

The effect of climate described in this report mainly involves unprotected environments.

Cereal Crops

Insect infestation of only major cereal types are considered: wheat, rice, corn (= maize), barley, oats, sorghum, millet and rye.

Insect species of stored cereals

(i) Principal pests - Destructive, occurring in large numbers usually throughout the year; usually attacking at least 1 major cereal; usually less than 5 in a country.

(ii) Major pests - destructive, occasional outbreaks in certain types of cereals at certain times of the year; usually less than 10 species in a country.

(iii) secondary pests - Common or occasional; economically less important than principal and major pests; may be up to 100 species in a country.

(iv) Associated insects - Incidental and sometimes common; of questionable economic importance.

Only the principal and major pest categories are considered in this study. All species referred to as insects or pests in the following pages refers to stored-product insect species. Today's highly developed global communication system allows frequent exchanges of large volumes of stored foods amongst various countries in several climatic zones of the world. Despite national quarantine and food inspection safeguards imposed by individual countries, some pests accompany foodstuffs and are accidentally introduced as new pests. Even in countries such as England and Japan in which insect quarantine has been enforced and records have been kept, new pest species have been reported at one time or another. Often, the geographical range of a single species, or, of a combination of stored-product species is restricted to 1 or 2 climatic zones. Birch [2] provides 2 reasons for such distribution: The food commodity is restricted, e.g. absence of *Corcyra cephalonica* (Stainton) in wheat-producing countries; and the weather conditions in surrounding climatic zones are unsuitable for its survival for at least part of its life. The species composition of a well-established insect fauna, however, often reflects the climatic condition of a region during a certain period. Although climate

provides the basic physical environment of the niches in which insects can flourish, it does not account for all the causes of an insect infestation; the causes, pathways and consequences of insect infestation are almost always interlinked with those related to grain harvesting, drying, moisture content, microflora, rodents, and design of granary structures. Nevertheless, because most of these variables are also affected by climate, climate's role is crucial in explaining many combinations of principal or major pest species in a country or a group of countries.

To understand how climate affects the ability of stored-product insects to succeed or fail as pests, one must first consider the behaviour of 2 crucial climatic variables, temperature and humidity, and then examine the relationships between atmosphere and water in relation to the biotic characteristics of the insect species and the food they infest.

Temperature

Temperature is a regulating factor in the survival, development and reproduction of all organisms (food grains, microflora, insects and mites) and its effect is correlated with the amount of water present in the atmospheric air. When the temperature increases with the presence and intensity of solar radiation, latitude or altitude, the relative amount of water in the atmosphere decreases. High temperature accelerates the life processes of all organisms. Generally, stored-product insects develop progressively faster from 20 to 35°C, and die within 5 to 7 degrees below or above this range. Heat, either naturally or through artificial application, removes moisture from food grains to levels at which they will be immune from invasion by insects and other biotic agents.

Moisture

All organisms require water in varying quantities to survive and multiply. The exact quantity of water or the absolute moisture content expressed as grams of water vapor per cubic meter of air in the atmospheric air determines the level of biotic activity of an organism or insect. The water carrying capacity of air increases with a rise in temperature. For example, at 10°C air can carry about 10 g of water per m^3; at 38°C, 45 g per m^3 (Fig. 4). Because at 38°C atmospheric air carries only 22% (10/45 = 22% RH) of the initial amount of water that it could carry at the saturation point at 10°C., air shows a strong tendency to absorb water from the biotic materials (seeds, insects, fungi, etc.) it envelops. This process deprives the organism of vital water supply and retards biotic activity. As the atmosphere cools to 32°C - still with 10g of the initial water per m^3 - the air requires only 33 g of water per m^3 to saturate (10/33 = 33% RH); correspondingly, its tendency to acquire water is reduced, thereby increasing the availability of water to other material. In an atmosphere of constant absolute water content, the relative humidity of the air decreases with the increase in temperature; this linear relationship is shown in Fig. 5.

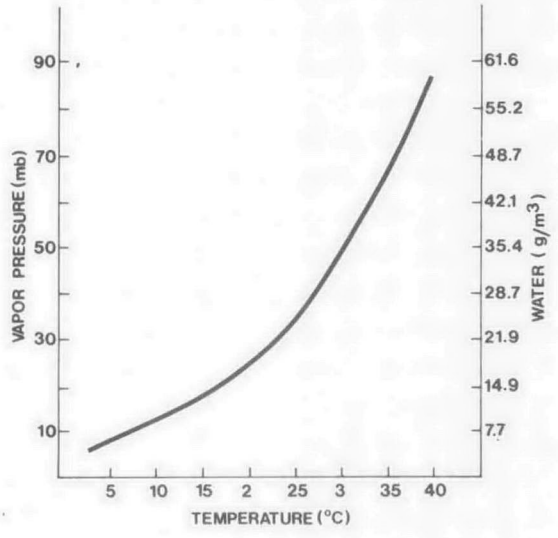

FIGURE 4. Water and vapor pressure saturation levels in atmospheric air at different temperatures. The carrying capacity of an absolute quantity of moisture by the atmospheric air increases with rising temperature resulting in air's greater demand for moisture from earth's water and organisms with watery body fluid [7].

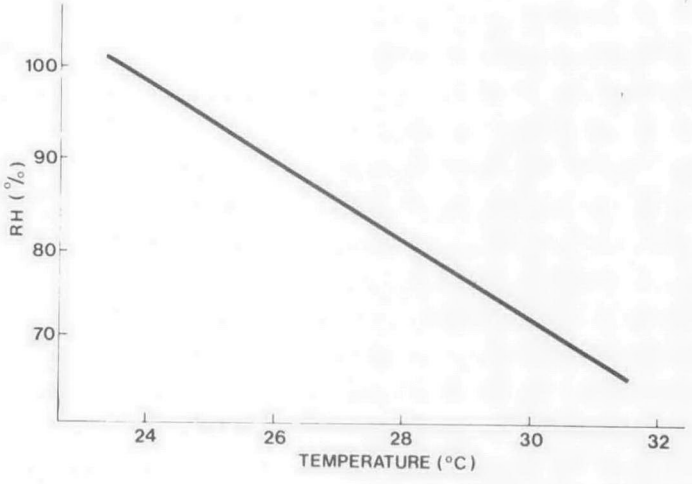

FIGURE 5. Linear relationship between relative humidity and temperature in an atmosphere containing a constant water content (21.7 g/m^3) [7].

Classes of climatic zones

In 1900 Walidmer Köppen developed one of the oldest systems of classifying climatic regions of the world based on 5 temperature limits. Although modified with changed boundaries, and greater sophistication - by accounting for moisture, frost, freezing, etc. - his system with 5 regions is still the basis of all global climatic classifications [3].

These regions are:

I. Tropical belt: 12 months above 20°C
II. Sub-tropical belts: 4-11 months above 20°C, 1-8 months from 10 to 20°C.
III. Temperate belts: 4-12 months from 10 to 20°C.
IV. Cold belts: 1-4 months from 10 to 20°C; 8-11 months below 10°C.
V. Polar belts: 12 months below 5°C.

Because most major stored-product insects do not multiply well enough to be pests below 20°C, they cannot infest stored products in cold and polar belts. They thrive and multiply best in the Tropical belt, and, to a lesser extent in the Sub-tropical and Temperate belts. Most cereals of the world, however, are neither produced nor stored in the Tropical belt. Humid middle latitude prairie grasslands, which comprise 7 percent of the land area of the earth and in which about two-fifths of the world's population lives, produce most cereal crops of the world such as wheat, barley, oats, corn and rye. Fortunately for mankind, home-grown stored cereals in this region are not often subjected to year-round heavy insect infestations similar to those common in the humid tropical belt. The climates of the areas of the world in which stored-products are infested by cosmopolitan insect species are the same as those of the farmlands of the world. Therefore I present a modern climate classification [4] of agricultural lands of the world (Fig. 6). Examples of insect species characteristic of these regions are also given.

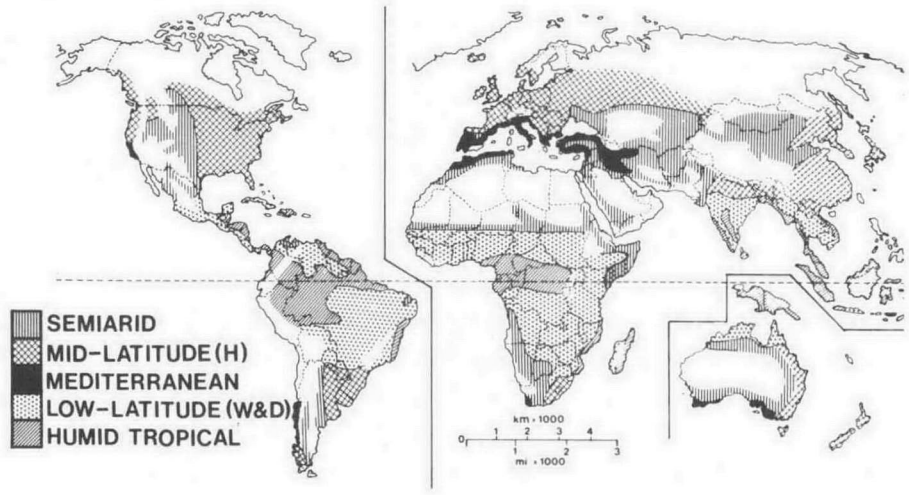

FIGURE 6. Climatic areas of world's farmlands [4].

Crop producing and storing areas classified by climate

I. Semiarid lands: Summers hot; winters in low latitudes hot year round, in middle latitudes cool to cold. Dry seasons with less than 38 cm (15 inches) rainfall.
Typical countries: Egypt, Sudan, Niger, Somali Republic,

Pakistan.
Major cereal crops: Cereals, especially millet and sorghum; often with irrigation.
Typical major storage insects: *Lasioderma serricorne*(F.), *Tribolium castaneum* (Herbst), *Sitotroga cerealella* (Oliv.)

II. Low-latitude Wet-and-Dry lands: All seasons warm or hot; wet season preceeded by dry seasons; slightly cooler in the low-sun period of the year.
Typical countries: India, Thailand, Brazil, Ghana, Burma, Ceylon, Indonesia.
Major cereal crops: Rice, corn, and other cereals.
Typical major storage insects: *Sitophilus oryzae* (L.), *Rhyzopertha dominica* (F.). *Corcyra cephalonica.*

III. Mediterranean lands: Warm to hot year round; summers dry; winters cool to mild, humid.
Typical countries: Italy, Greece, Turkey, Israel, Portugal.
Major cereal crops: Winter crops - corn, barley, oats.
Typical major storage insects: *Ephestia cautella* (Walker), *Sitophilus granarius* L.

IV. Humid Tropical lands: Hot and moist year round.
Typical countries: Congo, Columbia, Venezuela, Burma, Indonesia.
Typical cereal crops: Rice, corn.
Typical major storage insects: *S. zeamais* Motschulsky, *S. oryzae, S. cerealella*

V. Middle Latitude Humid lands: Summers warm to hot; winters cool to cold; 4 seasons distinct; frost-free period more than 90 days, varying with latitude; humid most of the year.
Typical countries: USA (North), USSR, China, Australia, West Europe, Canada, Japan.
Major cereal crops: Wheat, barley, corn and all other cereals except tropical crops.
Typical major storage insects: *S. granarius* (L.),*Oryzaephilus surinamensis* (F.) *Tribolium* spp.

This group has 4 subdivisions:

(i) Humid Continental with Short Summers
Major cereal crops: Spring wheat, barley, oats
Major storage insects: *Cryptolestes ferrugineus* (Steph.), *O. surinamensis*

(ii) Humid Continental with Long Summers
Major cereal crops: corn, winter wheat
Major storage insects: *S. oryzae, Tenebroides mauritanicus* (L.), *T. castaneum*

(iii) Humid Subtropical
Major cereal crops: wheat, rice.
Typical major storage insects: *O. surinamensis, S. granarius.*

(iv) West Coast Marine
Major cereal crops: wheat, rice.
Typical major storage insect: *O. surinamensis.*

Climatic effect at various levels of storage

Climate affects stored cereals and their insect pests at different levels, from producer to consumer, at which storage and transportation is carried out. The degree of climatic effect depends primarily on the extent of protection provided by man in terms of the design of granary structures, trucks, railway cars, ships' holds, and bulk or bag size. Fig. 7 illustrates a schema of levels of storage in developing countries of Africa [5] and Fig. 8 North America. Climatic effects is usually most severe at lower levels. Cereal harvest during unfavorable weather can seriously damage the keeping quality of the grain as it moves along the higher levels.

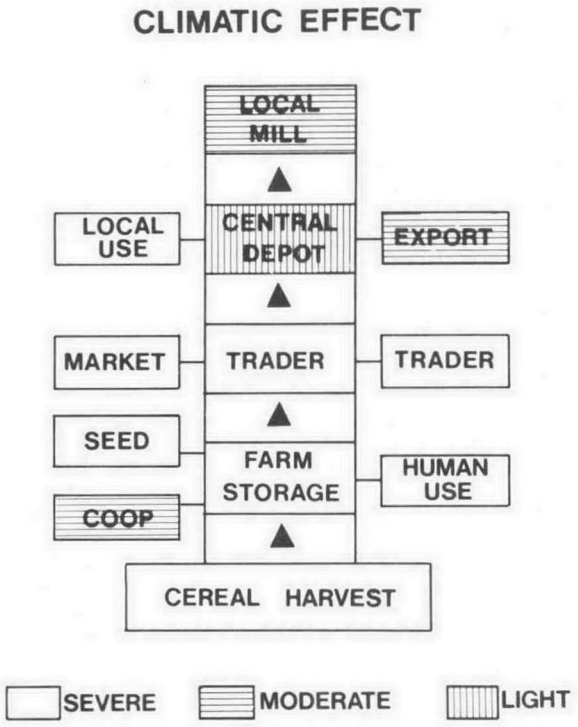

FIGURE 7. A schema of levels at which storage of cereals and climatic effect on the stored cereals and their pests occur in the African and other developing countries. Areas of severe, moderate and light climatic effect are shown by different hatchings [5].

Climatic plasticity index

Whether a stored-product species causes economic loss in a climatic zone in which there is adequate suitable food depends largely upon the physical limits and optimal ranges of temperature and RH within which the species can thrive and also on its intrinsic rate of increase (r_m). Although several major insect species occur in most food-producing and populated parts of the world, some species are particularly destructive in certain climatic zones but scarcely present in other zones. To cause outbreaks in any

climatic zone a species must be able to reproduce quickly in favorable periods of the year and survive with a sizeable residual population during unfavorable periods. Laboratory life history studies of 51 species of stored-product insects have shown that their rate of increase (r_m) is optimized within a narrow 3 to 4°C temperature range, usually at 60% RH or more [6]. The maximum temperature at which they will multiply is about 4°C above the optimum; most species do not reproduce fast enough to cause problems until temperature is about 3-5°C above the laboratory minimum and the RH at least 10% above the minimum [6].

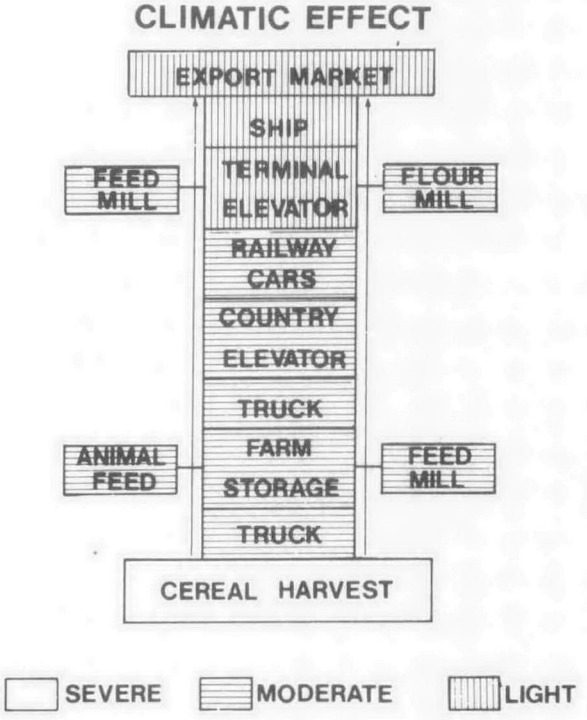

FIGURE 8. A schema of levels at which storage, transportation of cereals and climatic effect on stored cereals occur in North America and other industrialized, Mid-latitude Humid countries of the World. The levels at which severe, moderate and light climatic effect are shown by different hatchings.

The climatic, agricultural and socio-economic conditions of various parts of the world, being what they are, the reasons for the present distribution and clues for potential range of distribution of the storage species in relatively unprotected environments can be found largely in the inherent ability of a species to adapt, multiply and build large populations in an area. By integrating the laboratory data on the biology of each of 51 species I propose a 'plasticity index' statistic (I_p) to describe the potential ability of a species to adapt in various climatic zones. The higher the I_p value, the greater the climatic adaptability of the species.

Calculation of plasticity index

For a given species, assume the function relating ambient temperature to the intrinsic rate of increase, r_m is known; call it $r_m(t)$. Then the integral of the function represents an overall average reproductive potential for all temperatures and could be considered an index of plasticity of the species.

$$I_T = r_m(t)\,dt \quad \text{- (1)}$$

I_T is the index of temperature assuming equal weight to every temperature.

The figure could be made more precise for a particular climatic zone by integrating with respect to actual temperature distribution. If F_c is the probability distribution of temperature for a given climate c, we could calculate

$$I_{Tc} = r_m(t)\,dF_c(t) \quad \text{- - - - - - - - - - - - - - - - - -(2)}$$

If r_m for a species is not known at all temperatures, we can approximate it. The parameters as given by Howe [6] are:

t_o = minimum temperature for reproduction
t_1 = lowest limit of optimal range
t_2 = highest limit of optimal range
t_3 = the highest limit of reproduction is taken from Howe's [6] assumption as $t_2 + 4°C$.
r_m = the intrinsic rate of increase for a lunar month; that is the maximum rate at which a population with a stable age distribution can multiply, given unlimited food supply.

The function is approximated by the trapizoid (Fig. 9). I_T is then the area of the shaded region.

Hence $$I_T = \frac{r_m}{2}(t_3 - t_o + t_2 - t_1) \quad \text{- - - - - - - - - (3)}$$

To make the model more realistic we also include the effect of RH on this insect.

If h_o is the minimum RH and
h_1 is the maximum RH

Then $$I_H + I_T(h_1 - h_o - 5) \quad \text{- - - - - - - - - - - - - - - (4)}$$

The figure 5 is subtracted to account for the reduction of reproduction as the RH decreases to its minimum level.

Combining nos. (3) and (4).

The plasticity index $$I_p = \frac{r_m}{2}(t_3 - t_o + t_2 - t_1)(h_1 - h_o - 5) \text{--(5)}$$

The actual data for computation were taken from the published information of various workers summarized by Howe [6]. When a group of species is considered tolerant of low RH, 80 or 90% RH is used in the equation, similarly, for other species groups that need moderate RH and high RH 90 and 100% RH figures respectively were used.

A ranking of 51 species on the basis of their I_p values is given in Appendix I. Those species which have some of the highest I_p values - *Tribolium castaneum* (I_p = 588) and *T. confusum* (I_p = 478) - are in fact the most cosmopolitan pests of stored cereals and other foods. By contrast the rice moth, *Corcyra cephalonica* which is a specialized but dominant pest of rice only in Low-latitude Wet-and-dry lands, has an I_p value of only 110.

Trogoderma granarium which is restricted to a hot and dry climate also has a low I_p value of 97. The most destructive stored-product species, such as *Sitophilus oryzae* (I_p = 96) and *S. granarius* (I_p = 78), are not necessarily the most flexible species with regard to their ability to flourish in various climatic zones of the world.

Climate and cereal infestation patterns - Africa, Humid Tropical, Semiarid, Low-latitude Wet-and-Dry, and Mediterranean.

Africa has a wide variety of climates which provide 4 combinations of climatic conditions, hot/damp, hot/dry, cool/damp, and cool/moist/dry [5]. Hot/damp conditions cause most storage problem and cool/dry least problem. The main cereal crops are corn, rice, sorghum and millet. Harvesting occurs almost every month of the year depending upon the crop and region. In Nigeria corn is harvested in July and August, and rice in October-January. Hot and damp conditions and other local climatic and agricultural characteristics have allowed 2 insect species, *Mussidia nigrivenella* (Ragonot) and *Cathartus quadricollis* (Guerin Meneville) to predominate as pests of corn in Ghana, Togo and Nigeria (Fig. 10).

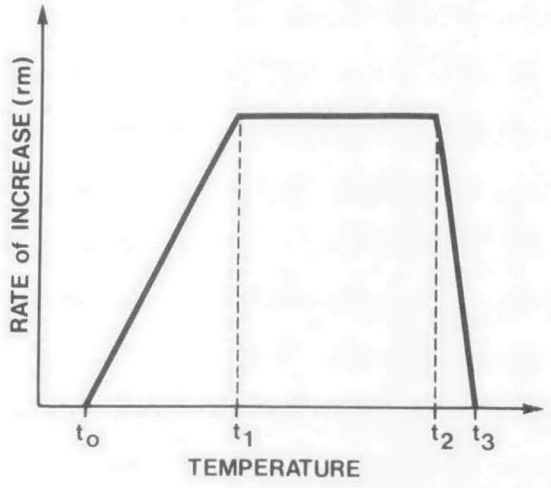

FIGURE 9. A schema illustrating how a climatic plasticity index (I_p) of a stored-product insect species can be calculated. r_m - intrinsic rate of natural increase per lunar month, t_o - minimum temperature for reproduction t_1 - lowest limit of optimal range, t_2 - highest limit of optimal range, t_3 - highest limit of reproduction incorporating Howe's [6] assumption as t_2 + 4°C. The central area indicates optimum multiplication of the species.

The voracious physitid moth larvae of *M. nigrivenella* which attacks mature but undried grains, often cuts deep groves right through the length of the corn cobs and consumes or damages as many as 20 grains. Larvae of *C. quadricollis* invade uninjured grains at 30% moisture but later are confined to damaged grain [7]. The major storage-insect species groups for selected countries of Africa are

given in Fig. 10. The data on dominant insects originates from various sources [P. E. Wheatley in litt., 5, 8-14].

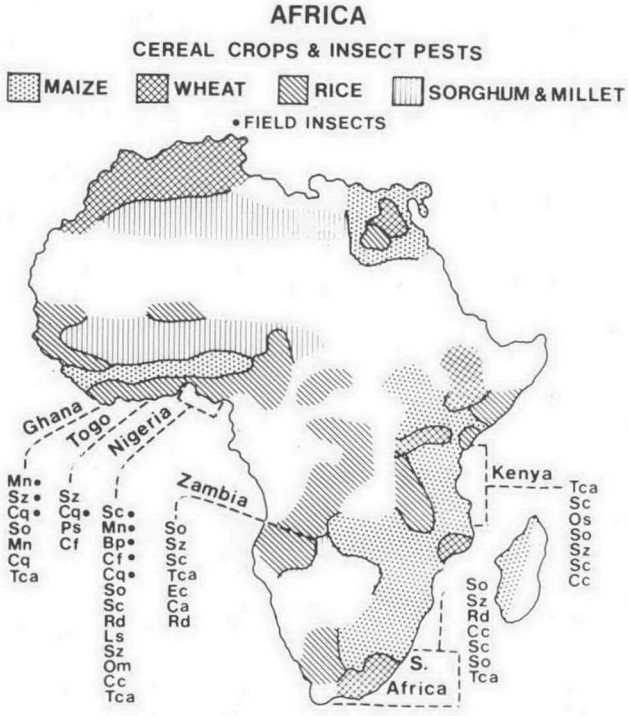

FIGURE 10. A map of Africa showing major cereal crop zones [5] and major stored-product insect species infesting cereals in field and in storage for selected countries. Each insect species is indicated by the first letter of its generic name (capital letter) and the first letter (lower case) of its specific name. The ranking of insect species is based on data provided by various workers.

Ghana is part of Low-latitude Wet and Dry and Humid Tropical lands of the world. Ghana's climate is unique, because it results from a clash of 2 extremely dissimilar air masses travelling diagonally from opposite directions: the cool and moist monsoon air masses which reach Ghana from the south west after long passage over the sea, and the hot and dry harmattan air masses which arrive from the northeast after passage over the desert. The 2 air masses meet in an area known as the Inter-tropical Convergence Zone (ITCZ). Their mixing generally produced an environment of warm moist air, although at times either of the 2 air masses may predominate. Intermittent solar radiation on this warm and moist atmosphere causes great diurnal fluctuations in RH allowing an ideal environment for fungal growth. Diurnal temperature fluctuation in the north ranges between 24 and 35°C, and in the south between 23 and 31°C [7].

Because the body temperature of cold-blooded animals assumes the temperature of their immediate environment, the metabolic

rate of insects in the Ghanaian environment increases with the rise of temperature at a rate dangerously higher than that with which the insect can cope. The crucial rate at which temperature affects insect survival and rate of increase can be understood by looking at Melanby's [15] temperature-and insect-development relationship diagram (Fig. 11). Insect development is quickly retarded with the rise in saturation deficiency that in turn results from increased temperature. The optimum for insect development in an atmosphere of constant water content, in which relative humidity declines with temperature rise, lies near the point at which the products of developing time x saturation deficiency is the lowest.

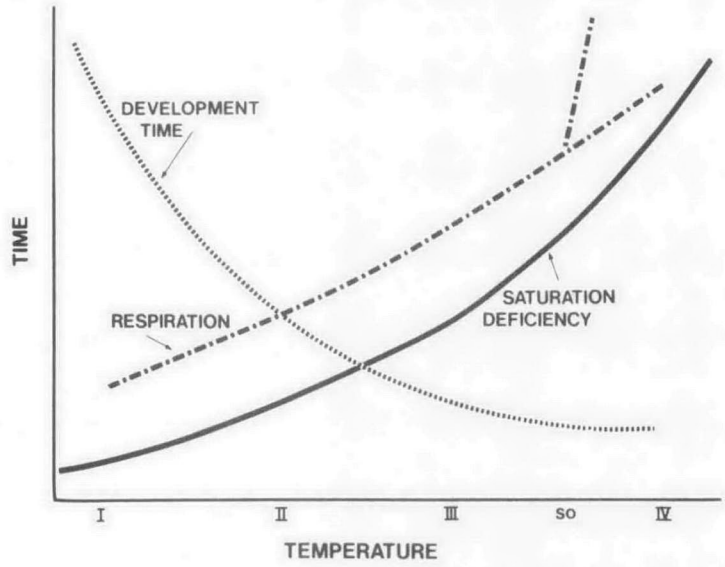

FIGURE 11. The effect of temperature on duration of development, rate of respiration, and saturation deficiency. At temperature I, development is stopped by cold, at IV by heat; the optimal zone of temperature is between II and III where the product of development time and saturation deficiency is lowest so indicates spiracular opening in certain insects [15].

The thermal death point is reached at an unbearably high level of saturation deficiency.

In Ghana, the optimum condition for the development of most storage microflora (25-35°C) falls within the normal ranges of RH and temperature in southern Ghana; only certain species of insects can make best use of the Ghanaian climate [7].

In the north, relatively drier conditions favor *Tribolium castaneum* and *Lasioderma* whereas in the south moister, relatively cool conditions favor *Sitophilus oryzae* [7]. Laboratory findings on the rate of increase explain the reason for this climatic separation of these dominant species. Fig. 12 shows that *T. castaneum* multiplies faster at higher temperature than *S. oryzae* [16, 17].

Uttar Pradesh, India, sub-climates within Humid Sub-Tropical zone

The Humid Sub-tropical zone of the Humid Mid-latitude lands are further divided into sub-climatic regions. For example, the cereal-producing Uttar Pradesh state in the north central part of India has 6 climatic zones each with a characteristic combination of dominant stored-product insect species. In a survey of endemic insect species in empty granaries Khare [18] found that *Sitophilus oryzae* (So), *Sitotroga cerealella* (Sc), *Rhyzopertha dominica* (Rd), and *Tribolium castaneum* (Tc) are the most common pests of paddy wheat, corn, millet and other grains grown in this region. Although food types and storage structures (approx. capacity 50-15000 kg) influence species distribution, climate seems

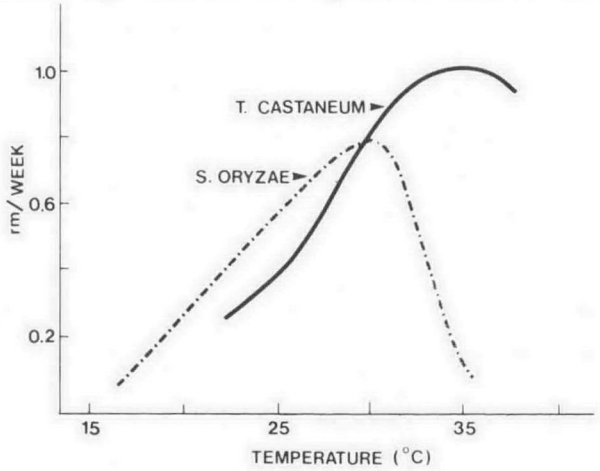

FIGURE 12. The effect of temperature on weekly intrinsic rate of increase of highly adaptable (*T. castaneum* and moderately adaptable *S. oryzae)* storage species occurring in Ghana [7, 16, 17].

to determine the pattern of combination of major species within a region. The 3 dominant species (listed in order of importance) in each region are given in Fig. 13. *Sitotroga cerealella* is a dominant pest in all regions except the cool hill area (about 3500 ft. above sea level) in which the *R. dominica* predominates. The notorious Khapra beetle, *Trogoderma granarium* Everts is dominant in the hottest and driest region in the south, Bundelkhand. The abundance of *R. dominica* and *O. surinamensis* (Os) in eastern, central and the western plain region - this area is dominated by *Sitophilus oryzae* (So), and *Sitotroga cerealella* (Sc) - is noteworthy. Obviously, certain combinations of major pest species in a region are the result of a wide variety of causes - agricultural and socioeconomic as well as climatic. But the latter cause has a dominant influence on the other two.

Australia - Mediterranean & mid-latitude Humid

The grain-growing areas of Australia have Mediterranean, Humid Subtropical and West Coast Marine climates (Fig. 14). Unlike Canada and U.S.A. where the harvest period is followed by cooler weather, the early summer harvest in Australia is followed by weeks

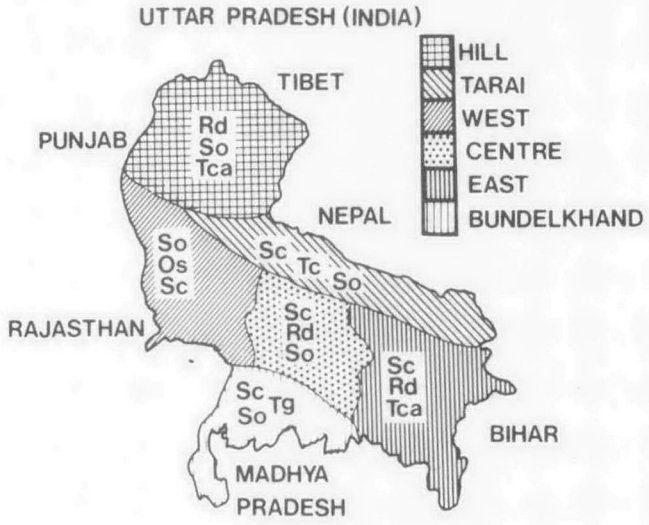

FIGURE 13. Six local climatic zones in the Uttar Pradesh State of India. Hill area is cooler and humid, Bundelkhand hot and dry, all other area hot and humid to wet. Each insect species is represented by the first letter (capital letter) of its generic name followed by the first letter (lower case) of its specific name [18].

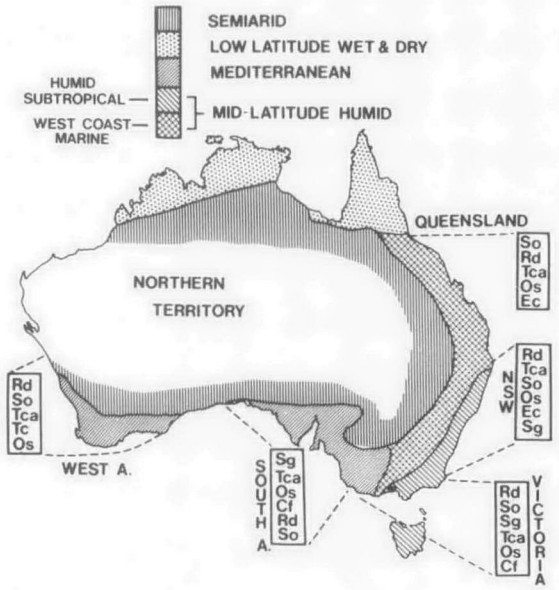

FIGURE 14. Climatic and major insect pest species ranked by local entomologists in order of importance - of cereal - and other crop producing areas of Australia. Each insect species is indicated by the first letter of its generic name (capital letter) and the first letter (lower case) of its specific name.

or months of warm to hot weather. Consequently, the major insect pests of stored grain - Australia has almost all major cosmopolitan

species - have a favorable initial environment to start infesting stored grain. Fig. 14 shows 5 combinations and ranking of storage species according to their economic importance (the data were provided by local entomologists for each of 5 states). The wheat-growing parts of Western Australia, which have a Mediterranean climate (winter rainfall and dry, warm summers but the region is also influenced by the adjoining hot and dry Semiarid zone), *R. dominica* ranks as the most serious stored-wheat pest, *S. oryzae*, *T. castaneum* and *O. surinamensis* follow in order of importance; and *S. granarius* is not among the major pests. In South Australia, with a moister Mediterranean climate, a recent survey by Birks (in litt.) has shown that 40% of farms were infested with *S. granarius*, 30% with *T. castaneum*, 29% with *O. surinamensis*, 16% with *Cryptolestes* spp., 15% with *R. dominica* and only 8% with *S. oryzae*. Victoria and NSW also have *S. granarius* as a high-ranking pest. It is noteworthy that *S. granarius*, is not important in Queensland. This may reflect the dominance of *R. dominica* and *S. oryzae*. However, *S. granarius* thrives in parts of NSW. H. G. Greening (in litt.) states the range of climatic conditions seems to provide perfect conditions for demonstrating the preferences of this species. Recently this species has been recorded on the western slopes of the Great Dividing Range, north to within 50 miles of the border with Queensland. Higher altitude with relatively cool and moist conditions favor *S. granarius*. A partial explanation for the success of *R. dominica* and the 2 weevil species obviously lies in the climatic effect. Most of Australia is warmer than the Canadian Prairies. Nevertheless, the highly adaptable *T. castaneum* and *C. ferrugineus*, occur in large numbers in both countries.

USSR - Mid-latitude Humid

The climate of most of the crop-producing areas of European USSR is Mid-latitude Humid (Continental) with short, hot summers, and long, cold winters. Weather during harvest (usually in August) greatly affects the initial storage condition of the grain. Grain is harvested at different moistures in different regions of the country. The initial storage moisture content of undried grain is below 15% in the Northern Caucasus, the Crimea and the Southern Volga areas which have longer and warmer summers [19]. It increases to 16-20% as we move northward through the Ukraine towards the Baltic Sea (Fig. 15). *S. granarius*, *C. ferrugineus* and grain mites are major pests in the cooler and moister northern areas whereas *O. surinamensis*, *Sitophilus* spp., *T. castaneum*, *S. cerealella* are the predominant species in stored grain in the South [19]. Climatic influence on storage insects is dramatic when one considers the number of generations per year for *S. oryzae*. This species has as many as 6-7 generations in the southern areas and only 1-2 in the northern areas (Fig. 15).

Burma - Humid Tropical and Low-latitude wet and dry

The rice-growing areas of Burma provide optimum conditions for development of almost all major storage insects. The mean daily temperature ranges from 25°C in January to 31°C in April.

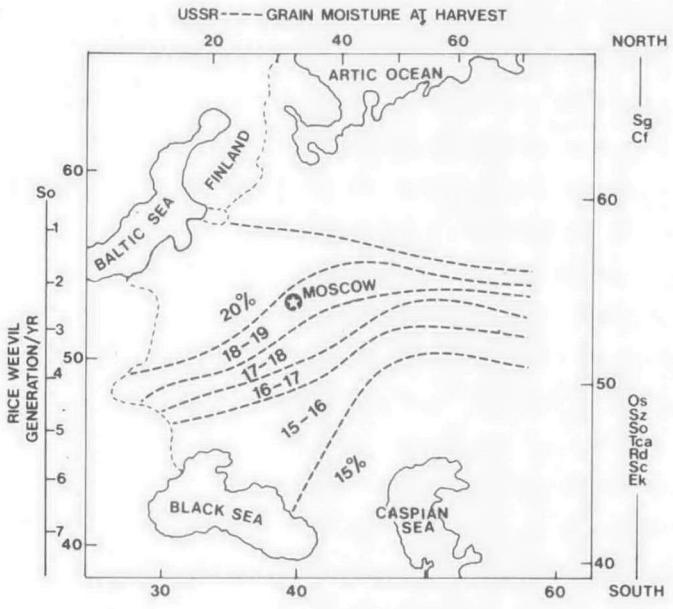

FIGURE 15. The levels of grain moisture at harvest and the major stored-grain insect species in the European USSR. The scale on the left indicates how *S. oryzae* has fewer generations as one moves northward. The first letters of the generic and specific names are used to indicate each insect species [19].

The RH ranges from 61 to 68% in the relatively dry winter and is about 90% in the monsoon months of May to September. *Corcyra cephalonica*, *S. oryzae*, *T. castaneum*, and *S. cerealella* are among the several dominant pests of stored grain [20]. It is noteworthy that Burma's top pest, *C. cephalonica*, is scarce in the rice growing area of the Northern Hemisphere. The ubiquitous and highly adaptable species, *T. castaneum* and *C. ferrugineus*, are also pests of stored grain in Burma.

Argentina - Mid-latitude Humid, Humid Subtropical

Argentina has a Humid Sub-tropical climate. Its main wheat-producing zone, 700 miles between 30° and 40° latitude, is limited in the north by a combination of high temperature and high humidity in the growing season, in the west by arid desert conditions, and in the south by drought and low temperature. The winters are mild except in the southern part. Harvesting is done in November and December. Harvested grain is stored in sacks in local granaries and warehouses, in bulks in elevators in the interior and in large terminal elevators at the seaport. Various major storage species occur in relation to the climatic and storage conditions. A major pest is *S. granarius*, which prefers cooler climates than other *Sitophilus* spp., it is most common in the cool southern areas where it completes 6-7 generations per year. Other major pests are *S. oryzae*, *S. cerealella*, *R. dominica*, *T. castaneum*, *E. cautella*, *O. surinamensis*, and *C. ferrugineus* [21].

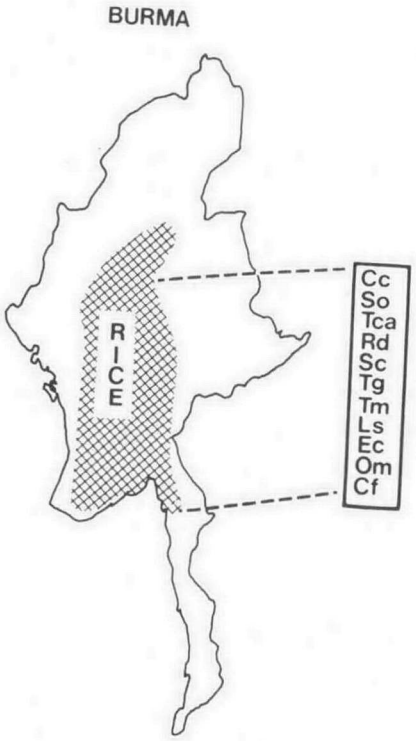

FIGURE 16. The rice growing area and major stored-product insect species in Burma, ranked in order of importance [20].

Canada and the United States - Mid-latitude Humid

The climatic subdivisions, crop growing pattern and the major pests of America north of Mexico are given in Figs. 17 and 18.

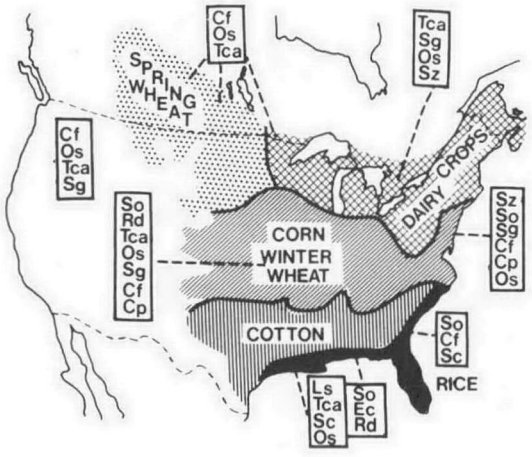

FIGURE 17. The major crop growing areas of Canada and the United States.

Most Canadian grain is produced in the 3 Prairie Provinces of

Manitoba, Saskatchewan, and Alberta. The Canadian Prairies have a Humid Continental "grassland" type of climate; the winters are long and cold, summers are short and hot. Harvesting takes place during August and September. In winter, temperature often falls below the minimum limits of reproduction, development, and survival of most destructive cosmopolitan stored-grain species, while exceeding the maximum limits for certain species in summer. Only cold-hardy and adaptable species such as *Cryptolestes ferrugineus*, *Tribolium castaneum* and *Oryzaephilus surinamensis* flourish in this climate (Fig. 18). The Pacific north-west state of Washington, and the spring wheat growing states, North Dakota, Minnesota have the same combination of pest species in farm-stored grain; but because the climate of Washington is milder and more moist, *Sitophilus granarius* also appears in the combination [22].

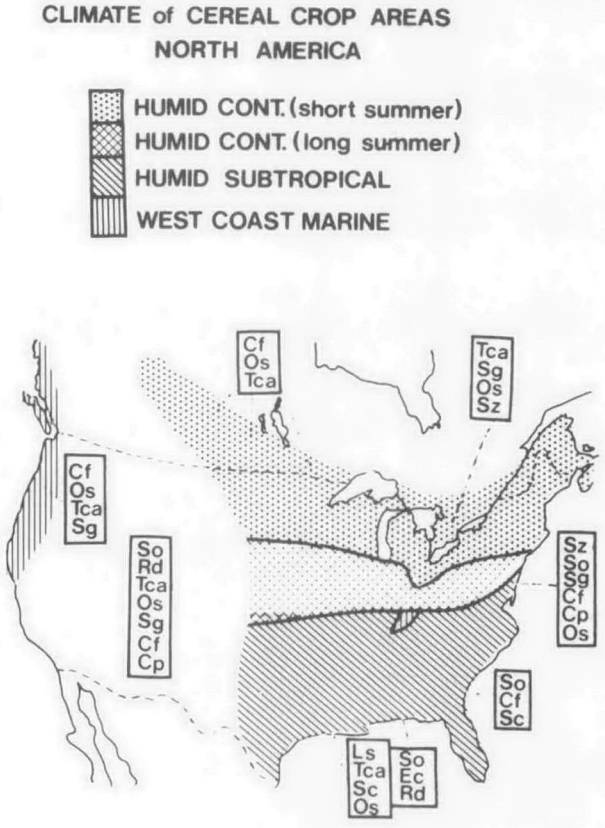

FIGURE 18. The climatic areas of Canada and the United States. Major insect pests and their estimated ranks are given for selected areas. The first letters of the generic (in capital letters) and specific names are used to indicate each insect species.

The winter-wheat growing states such as Kansas and wheat- and corn-growing states of the eastern part of the United States have a combination of major pests that includes *S. oryzae*, *R. dominica* and *T. castaneum* (23]. In the corn belt, *S. zeamais* is a dominant insect pest. In the southerly Humid Subtropical areas along the

Gulf coast *Lasioderma serricorne, T. castaneum, Sitotroga cerealella, O. surinamensis* and *Sitophilus oryzae* are among the top-ranking pests [24].

Interference of climatic effect

Although climatic data for a geographical location gives an estimate of the performance of stored-product insects in that area, allowances must be made for the factors that usually reduce the impact of a climatic variable. The size of the grain bulk and the granary structure are 2 such important factors. The larger the grain bulk the greater is the protection of insects from climate. Thus climatic effect becomes most pronounced in small granaries. By computer simulation of temperature data in circular metal granaries of various sizes, filled with wheat, Yacjuk [25] showed that the temperature effect was most pronounced in granaries up to 4-meters in diameter. When freshly harvested grain is stored at 25° in Winnipeg, it takes 90 days for the center of a bin 4-m in diameter to cool below 20°C. For the comparable figure for a bin 6-m in diameter is 150 days; 8m - 225 days, 10m - 329 days, 12m - 553 days. Grain cools fastest and remains cooler longest in regions such as Winnipeg and Thunder Bay which have a Temperate Continental Climate. Milder climates of coastal cities such as Montreal and Vancouver is reflected in the slower cooling of the grain.

Prediction of insect outbreaks from climatic data

Multivariate summarizations of selected climatic variables and insect infestation data can be used in predicting stored-product insect infestations in small parcels of grain in large geographical areas. Sinha et al. [26] determined the basic relationship between abiotic climatic variables and the spoilage of stored grain by insects, mites and microorganisms and ranked these for the 41 crop districts in the Prairie Provinces of Canada. Principal component (PCA) and canonical correlation analyses were applied to data from 3 crop years (1967-1969). The climatic variables consisted of mean temperature, precipitation, and number of days above 20°C for July, August and September for each crop district. The biotic variables were crop district, means of insect and mite infestations, and grain heating reports from farmers' granaries communicated to 2522 managers of country elevators. PCA indicated that warmer weather increased *Cryptolestes ferrugineus* infestation, whereas cooler weather increased infestation by mites and secondary insect pests. The first and second principal component values for each crop district were ranked and plotted on a climatic map of the Prairie Provinces [26]. The ranking showed that the incidence of hot spots and arthropod infestations was highest in the Sub-boreal and Humid southeastern sub-regions, whereas the incidence was lowest in the Dry Belt sub-region. *C. ferrugineus* was most common in the Humid southeastern sub-region.

CONCLUSIONS: Although several of about a dozen major species of stored-grain insects occur in most countries of the world, their abundance and the groups in which they infest, often reflect the

climatic characteristics of the country or of regions within it. For example, the major storage pests of stored cereals in the Mid-latitude Humid areas (Continental Temperate climates) with short summers in the Canadian Prairies and in the northern United States are *C. ferrugineus*, *T. castaneum* and *O. surinamensis*, whereas those of the more southerly Mid-latitude Humid climate with long summers in Kansas, Illinois and Iowa are *Sitophilus zeamais*, *S. oryzae* and *R. dominica*.

In the Northern Hemisphere, the most productive cereal-growing regions within cooler Mid-latitude Humid areas - Canada, U.S.A., France and USSR - provide less than ideal conditions for the multiplication of the most destructive storage insects. In the Southern Hemisphere, similar regions with warmer climate - Argentina and Australia - provide near optimum conditions for multiplication of the most destructive storage species.

Farming areas with Low-latitude Wet and Dry and Humid Tropical climate, such as those in Nigeria, Bangladesh, Burma and Indonesia, provide optimum conditions for the multiplication of almost all destructive storage species.

Climate affects both seeds and the insects which feed on them. Moisture is absorbed by or evaporated from stored grains because of climatic variations. Climate and weather affect the population density of a pest species by affecting its endocrine system, survival, development and reproduction.

A climatic plasticity index (I_p) of a storage species - when calculated from laboratory data on the physical limits, optimum range of temperature and RH, and the intrinsic rate of increase (r_m) - can largely explain the present geographical distribution and the potential for future range of a stored-product species. Some of the species with high I_p values - *T. castaneum*, *C. ferrugineus* and *O. surinamensis* - are in fact the most cosmopolitan storage insect pests. *C. ferrugineus*, which is the principal pest in the cold Canadian Prairies, is also a pest of stored grain in the Low-latitude Wet and Dry, South Africa and hot, Humid Tropical Burma. *T. castaneum* occurs in almost any combination of climates - hot, cold, dry, humid, wet - in which grain is stored.

In grain storage systems in which cereal is repeatedly and intermittantly stored and transported at various stages from producer to consumer, the climatic effect is usually more pronounced in the initial stages of the movement-storage-movement sequence.

PROPOSALS FOR FUTURE: Infestation of stored grain is a complex process which is preceded and followed by equally complex interactions of cereals with a diverse array of abiotic and biotic variables. To prevent and control insect infestations measurement and manipulation of climatic variables can be crucial, because all pest infestations of stored cereals occur against a background of cereal-climate relationships. The patterns of cereal production, storage and distribution must be integrated with the patterns of survival, development, reproduction and transportation of stored-product insects to permit development of a global strategy for

prevention and control of insect pests. As a first step toward this objective climatic data for each country and for each type of cereal, and for the pests of each cereal should be determined. Laboratory and field data on insect biology, and ecology - much of it already collected - should be synthesized and correlated with meteorological data. Prediction models and pest management systems for the combination of insect species, characteristic of each region, should be developed. Chemical and other methods of control should be applied within the context of bioclimatic evaluation of a group of stored-product species within a geographical or political region.

In selecting locations and structural designs for granaries, bioclimatic considerations should be given as much importance as the logistic and economic considerations. Bioclimatic considerations should include the proposed plasticity index of endemic and potentially dangerous species.

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APPENDIX I: Climatic plasticity index (I_p) values for 51 species of stored-product insects.

Tribolium castaneum (Hbst.) 700, *Anagasta kuehniella* (Zell.) 600, *Tribolium confusum* Duv. 570, *Cryptolestes ferrugineus* (Steph.) 570, *Oryzaephilus surinamensis* (L.) 500, *Callosobruchus maculatus* (F.) 550, *Cadra cautella* (Wlk.) 575, *Sitotroga cerealella* (Ol.) 550, *Carpophilus hemipterus* (L.) 550, *Cryptolestes turcicus* (Grouv.) 475, *Dermestes maculatus* (Deg.) 360, *Callosobruchus rhodesianus* Pic 230, *C. chinensis* (L.) 315, *Oryzaephilus mercator* (Fauo.) 210, *Acanthoscelides obtectus* (Say) 275, *Plodia interpunctella* (Hb.) 330, *Dermestes frischii* Kug. 285, *Cadra calidella* (Gn.) 230, *Necrobia rufipes* (Deg.) 250, *Lasioderma serricorne* (F.) 200, *Araecerus fasciculatus* Deg. 360, *Rhyzopertha dominica* (F.) 190, *Zabrotes subfaciatus* (Boh.) 190, *Trogoderma granarium* Everts 131.25, *Sitophilus oryzae* (L.) 275, *Ephestia elutella* (Hb.) 165, *Cryptolestes capensis* (Waltl) 105, *Gnathocerus cornutus* (F.) 180, *Sitophilus granarius* (L.) 172.5, *Cryptolestes ugandae* Steel & Howe 150, *Corycyra cephalonica* (Stnt.) 110, *Latheticus oryzae* Waterh.

95, *Endrosis sarcitrella* (L.) 330, *Cryptolestes pusilloides* (Steel & Howe) 105, *Cryptolestes pusillus* (Schon.) 100, *Stegobium paniceum* (L.) 67.5, *Gibbium psylloides* (Czenp.) 42, *Caryedon gonagra* (F.) 42, *Ptinus tectus* Boield. 42, *Mexium affine* Boield. 23.75, *Ptinus fur* (L.) 23, *Stethomezium squamosum* Hinton 21, *Niptus hololeucus* (Fald.) 21, *Trigonogenius globulus* Sol. 15, *Pseudeurostus hilleri* (Rttr.) 15, *Ptinus clavipes* Panz. 10, *P. sexpunctatus* Panz. 9.5, *Tipnus unicolor* (Pill. & Mitt.) 9, *Hofmannophila pseudosprettella* (Stnt.) 19, *Ptinus pusillus* Sturm. 5.

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