Non-linear Relationship between Food Resource Exploitation and Population Density of Stored-product Pests*

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Abstract

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The main current strategies (IPM, HACCP) to control pests in stored food products are based on critical thresholds derived from pest population density. These thresholds usually do not consider cumulative effects of earlier pest infestation although injuries caused by biotic pest organisms to stored food commodities are irreversible. We present conceptual and illustrative models showing that population size indices, in contrast to cumulative (population history) indices, could (i) underestimate critical thresholds if pest population can grow exponentially and (ii) provide incorrect information about the level of stored food damage if pest population density can fluctuate. The importance of entomological food microanalysis and continual "cumulative monitoring" based on trapping is discussed with respect to HACCP and IPM programmes in stored food products.

Key words: pest populations dynamics; population history; cumulative population indices; thresholds; decision making

Arthropod pests cause immense losses annually due to their feeding and contamination of human food resources world-wide. As a consequence, many different management strategies are used to control these pests. Since the 1950's so called "Integrated Pest Management" (IPM) strategy, integrating economic and ecological principles, has become a fundamental paradigm for pest management in agriculture (STERNS *et al.* 1959). This strategy was so influential that many non-agricultural areas of pest control (e.g., urban and medical entomology) have been trying to adopt and/or adapt the IPM ideas. During the last 2 decades HACCP (Hazard Analysis and Critical Control Points) as a specific safety system to protect food from harmful organisms and toxicants has been developed by food industry researchers (SCHOTHORST 1989; DUNAIF, KRISINSKI 1992). Most recently JANG and MOFFIT (1994) outlined a promising "systems approach" to quarantine safety defined as "The integration of those pre- and post-harvest practices used in production, harvest, packing and distribution of a commodity which cumulatively meet the requirements for quarantine security". Both IPM and HACCP decision-making processes are similar in terms of using critical thresholds based on population density of the pest (HAGSTRUM, FLINN 1996). Critical thresholds (i.e., economic injury threshold/level – EIT/EIL, aesthetic injury threshold – AIT, economic threshold – ET, action threshold – AT) are mostly characterised by the presence of certain "critical number" of living pest animal at which some serious losses/problems to human resources appeared (EIT, AIT) or some protective measures must be applied (AT, ET) (for detailed description see FLINT, VAN DEN BOSCH 1981). Various pheromone and pitfall traps, probes, sieves and sound detectors are employed for estimating population density of pests in stored grain and food industry premises (COGAN *et al.* 1991; SUBRAMANYAM, HAGSTRUM 1996; STEJSKAL 1997, 1998). However, critical thresholds based solely on population density are applicable only in the case of protection of resources with auto-reparation or compensation ability (e.g., plants, trees), where the pest population density more or less realistically reflects the actual level of damage of the food resource. This is not true about many stored food products which have no auto-reparation or compensation ability although some of them are living organisms, e.g., seeds of cereals and pulses. Except direct measurements of damage only "population history" indices can help to estimate the level of actual cumulative losses. Cumulative nature of losses and injuries caused by arthropod pests to stored food ce-

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reals is often overlooked, especially at the farm level. HAGSTRUM and FLINN (1996) reported that in some countries (e.g., USA) food industry plants use as a food quality criterion not only (i) numbers of living pests but also (ii) level of food injury and (iii) numbers of arthropod fragments and other organic filth per sample. Nevertheless, information on the relationship among these criterions (i–iii) is scarce if any.

The aim of this work was to present conceptual models demonstrating the differences in estimation of critical population thresholds based on population density vs. cumulative population indices. I should like to stress that presented graphical models are illustrative only. Some of them are applicable only to organisms with discrete non-overlapping generations which is not often fulfilled in stored product pest arthropods developing continually with overlapping generations.

Models

Population biology of animal pests is modelled in various ways which are treated in detail in many papers and textbooks (e.g., HASTINGS 1997; BEGON, MORTIMER 1996). Similar models used in food-protective microbiology were recently reviewed by ERBAN and ČERNÝ (1998).

Basic equation for population changes between (non-overlapping) generations can be expressed :

$$N_{T+1} = RN_T \quad [1]$$

where: N – number of pests (= population size)
T – generation
R – net rate of population changes per generation (T)

This equation gives following predictions: $N_{T+1}/N_T > 1$ population grows without bounds, $N_{T+1}/N_T = 1$ population size is stationary and $N_{T+1}/N_T < 1$ population decreases and approaches the zero.

Critical threshold of the particular pest species population is estimated from specific damage. It is assumed that the relationship between population density and damage is linear in seed/fruit feeding pests (MUMFORD, KNIGHT 1997). Over the period (usually from 3 months to 3 years) of storage of grain or other food commodities several generations of stored-product pests can develop and extinct. Not surprisingly, the degree of food-resource exploitation (level of injury) does not correspond to current population density but to a sum of all individuals which has developed on the resource. Therefore we suppose that it would be useful to discriminate the following population indices: (i) number of living animals ($N_0 = N_{T_0}$) at which the population starts at T_0, (ii) population density (N_{T_n}) at T_n, and (iii) cumulative number of individuals (C_{T_n}) of population, which developed in the interval $T_0 - T_n$.

Then C_{T_n} is simply obtained by:

$$C_{T_n} = N_{T_0} + N_{T_1} + N_{T_2} + \ldots + N_{T_n} = \sum_{T=T_0}^{T_n} N_T \quad [2]$$

Assuming that each individual consumes a constant amount of food resource (d) during its development then the expected level of food-resource exploitation (E_{T_n}) can be calculated as follows:

$$E_{T_n} = \sum_{T=T_0}^{T_n} N_T \, d = C_{T_n} \, d \quad [3]$$

It is obvious that if the resource has no ability for auto-reparation, as it is in stored food product, then the losses caused by pest feeding have irreversible and cumulative nature. Thus the food-resource exploitation (losses) cannot decrease between consequent generations (from T_n to T_{n+1}) even if the population is stationary or decreasing ($N_{T_{n+1}} \leq N_{T_n}$) (Fig. 3):

$$E_{T_n+1}/E_{T_n} \geq 1 \quad [4]$$

The difference in estimation of the economic injury threshold (EIT) when using population numbers (N) and population cumulative numbers (C) indices

Fig. 1 presents a model of a simple exponential population growth (equations 1 and 2) showing differences between "N" and "C" indices in the particular generations (T) and the implications for economic injury thresholds (EIT). For example, put arbitrary an economic injury threshold equals to 150 emerged pest individuals (EIT = 150) per weight/volume unit of the particular food-resource. Then in simulation model (R = 2, N_{T_0} = 5) (Fig. 1) the critical EIT_{150} value is indicated 1 generation earlier by cumulative population indices (C_{T_n} = 150 at T_n = 3.91) than current population size indices (N_{T_n} =150 at T_n = 4.91). It meant that as soon as the population size (N_{T_n}) reached 150 individuals the "real" economic threshold (EIT_{150}) was

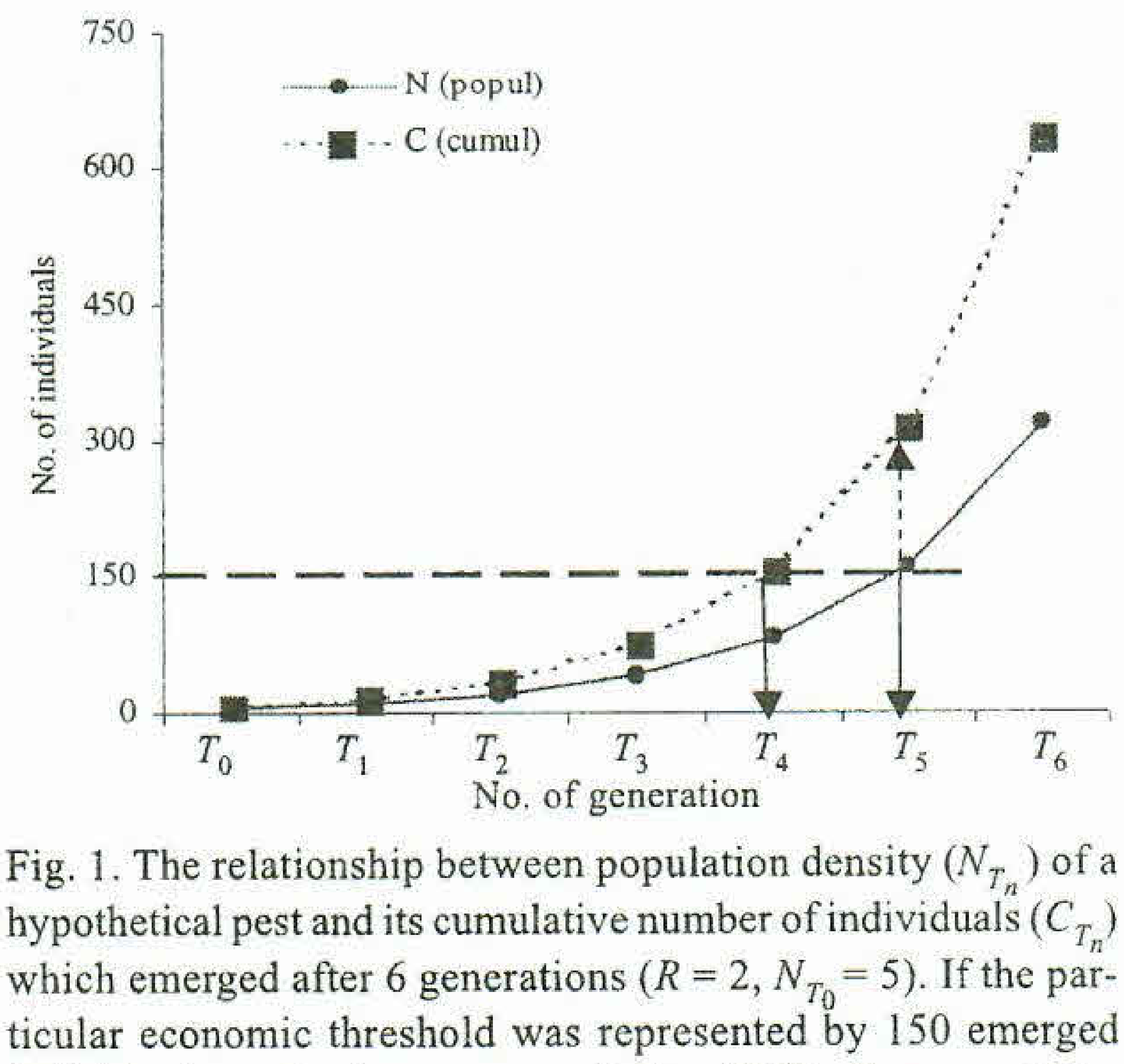

Fig. 1. The relationship between population density (N_{T_n}) of a hypothetical pest and its cumulative number of individuals (C_{T_n}) which emerged after 6 generations (R = 2, N_{T_0} = 5). If the particular economic threshold was represented by 150 emerged individuals per food-resource unit, then "N" indices would indicate this level of damage with one generation delay against the "C" indices (arrows)

exceeded ca. two times. Threshold based decision making and predictive modelling should therefore include not only population size (N_{T_n}) but also cumulative population indices (C_{T_n}) in some instances.

Does low pest population always reflect low food resource damage?

The pest populations are not always exponentially growing as shown in the Fig. 1 but they frequently fluctuate. I would like to draw attention to the fact that pest population fluctuations are another important source of inconsistency between present population size (N) and food resource exploitation (E) of stored food product. Due to fluctuations the identical level (L) of population density can appear several times (t_1, t_2, t_3, t_4) during the course of population development (Fig. 2) – at each time, however, the level of stored food resource exploitation is different.

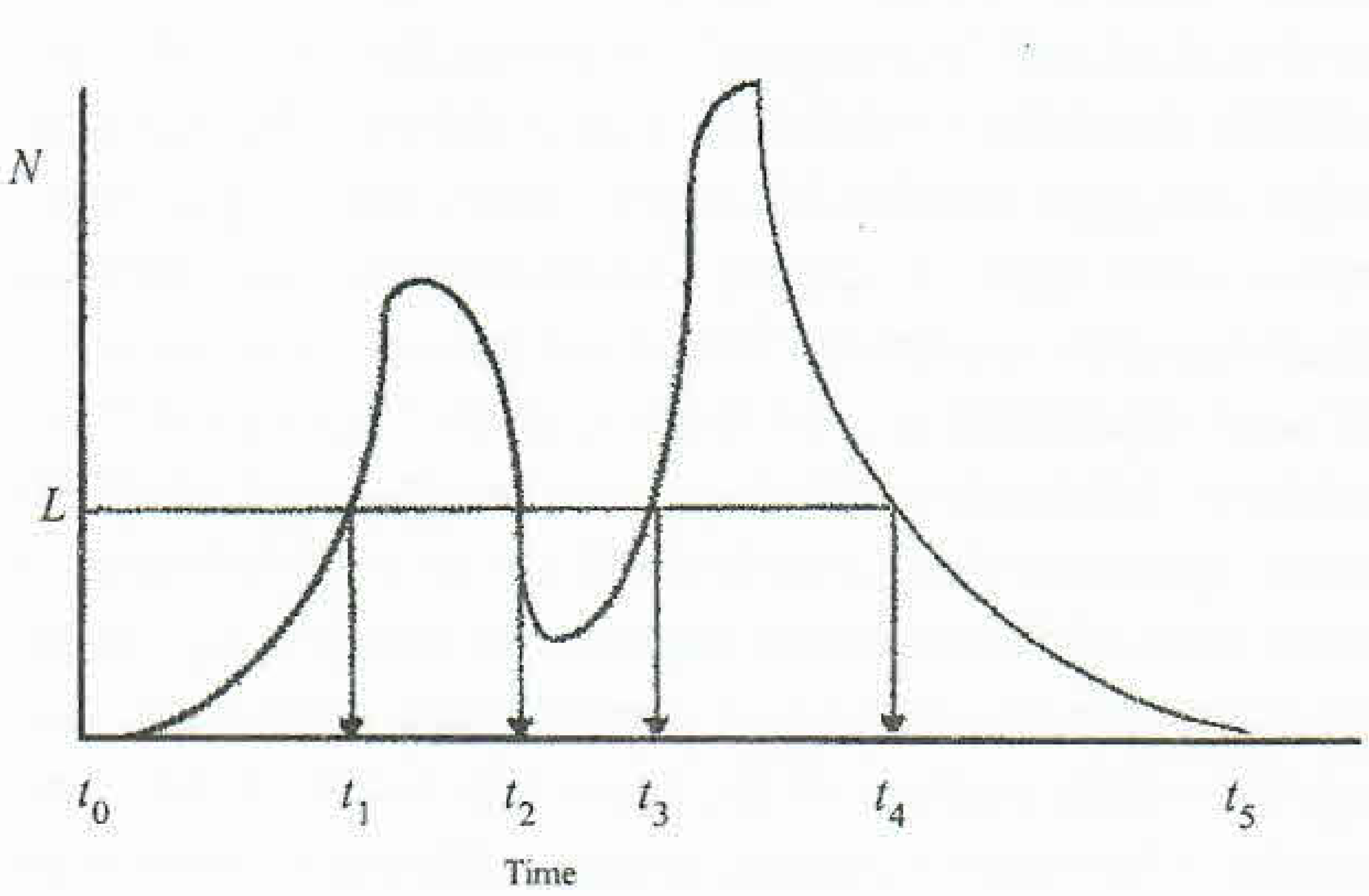

Fig. 2. Identical level (L) of pest population density (N) can appear several times (t_1, t_2, t_3, t_4) during the course of development of fluctuating population density

From Fig. 3, which presents a schematic graphical model (equations 1–3) demonstrating the level of the exploitation of food resources under various pest population dynamics (exponential growth, equilibrium, decrease and extinction), it is evident that the values of N_{T_n} and E_{T_n} copied the same trend whereas C_{T_n} and E_{T_n} did not. Even the zero population level ($N_{T_n} = 0$) may occur under substantially different situations in terms of resource exploitation: (i) zero exploitation (T_0) or (ii) partial or total exploitation of food resource (T_c) when pest population becomes extinct due to eradication (e.g., fumigation, cooling) or from starving. Similarly, population density of hundred just arrived immigrants ($N_{T_0} = 100$) can be present at the moment when the food resource has suffered little or no damage ($E_{T_0} \cong 0$) so far.

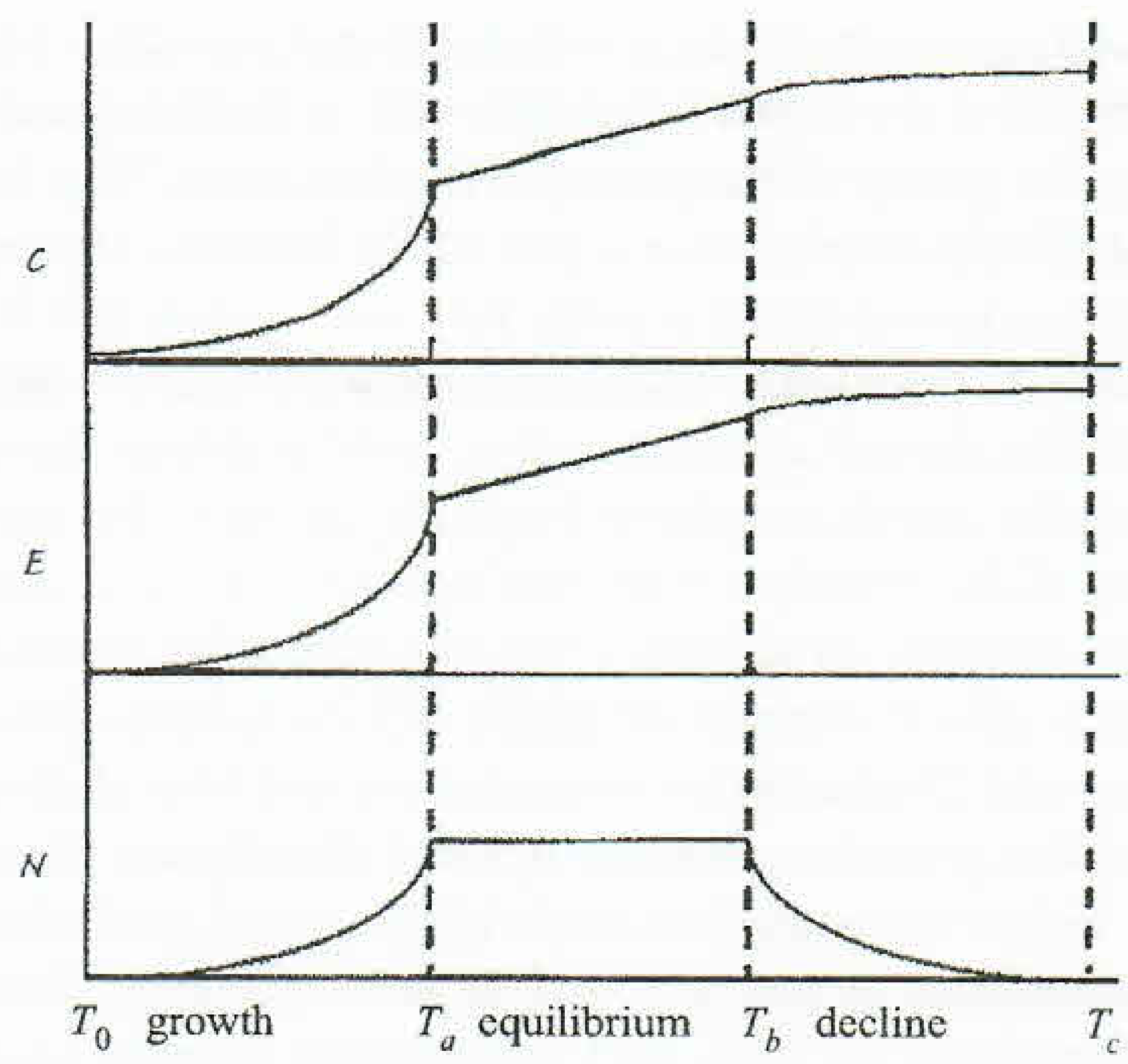

Fig. 3. The graphical demonstration of the relationships between indices of population density (N_{T_n}), cumulative population density (C_{T_n}) and food resource exploitation (E_{T_n}) under various pest population dynamics: growth ($T_0 - T_a$) equilibrium ($T_a - T_b$), decrease and extinction ($T_b - T_c$) (Curves are smoothed to be continual)

DISCUSSION

Successful field agricultural pest control strategies, "field-IPM" concept in particular, are sometimes uncritically overtaken into different areas where protection of human resources against pest is necessary. The critical thresholds for pests in the field agriculture are based on population density which is usually more or less correlated with the current level of plant damage due to gradual compensation growth. However, stored food resources have no auto-reparation mechanisms and the use of critical thresholds solely based on the "N" indices could bring some problems. Aforesaid we demonstrated that in exponentially growing pest population the population size (N) indices may be unrealistic in terms of estimation of real economic injury threshold unlike "C" population cumulative numbers indices. We also argue that pest density in fluctuating populations (Fig. 2, 3) may tell us very little about actual injuries to food products under certain circumstances. However, it is necessary to stress that "N" indices are very important for pest population predictions and thus for the estimation of future hazards. Our conclusions may have some practical implications for critical thresholds and decision-making process to control stored food product pest.

Basically, there are two approaches to establish EIT in stored grain for human consumption at the national and international agricultural commodity market nowadays. **First approach** coins the zero pest arthropod tolerance **(EIT = 0)**. This "total insurance" approach, which is typical of Europe including the Czech Republic, assumes that buying or selling the particular commodity without any pest arthropod also automatically ensures food commodity with zero level of injury. As a consequence, entomological microanalysis (filth testing) is not usually performed along the whole food production chain and critical thresholds for dead pests, pest fragments, faeces and allergens in human food commodities are not available in most of these countries. However, as shown in simulation models, population density (even zero pest density!), contains poor information about past infestation and, as a consequence, about the quality of the protected food resource. This fact is intuitively employed as a part of the business strategy while marketing stored cereals. It is well-known that it is possible to repeatedly kill insects, blow off or sieve them out during the storage, especially carefully shortly before selling the cereals in order to drastically decrease the probability of the detection of the pest infestation by a customer. For example ARMITAGE (1994) found that the aspirated sieve is able to remove all adults of *Cryptolestes ferrugineus* and *Oryzaephilus surinamensis* and over 95% of *Sitophilus granarius* from the infested stored grain. However weight (consumed and injured grain) and qualitative (contamination by faeces, body fragments, allergens, chemicals produced by pests etc.) pest-induced damage accumulated during the whole storage period of the infested food commodity could be removed only in part. Nevertheless, according to HACCP philosophy the safety and quality of human food must be ensured by monitoring and checking critical limits of safety and quality at each "critical control point" of the whole food processing chain. Non-linear relationship between level of damage and population density of some stored-product pests makes the "*N*-indices" fairly unsafe as an exclusive criterion of the present quality of food resource. To reach the goal of safety trough HACCP philosophy in any particular food production plant, besides monitoring pest population density ("*N*"), some form of direct motoring of the level of the damage and contamination of food inputs and outputs should be established and maintained.

The **second approach** permits non-zero pest population density (**EIT > 0**). HAGSTRUM and FLINN (1996) reported that there is 0.1–5 pest per kg of grain tolerance in the USA – any food commodity infestation is however penalised to cover the cost of future pest control and cleaning measures. In connection with non-zero EIT the US food industry plants frequently check safety and quality of food products by methods of microanalytical entomology, which includes estimation of pest presence or density and of its fragments by filth-flotation test (HELRICH 1990), ELISA tests and direct counting of the number of insect damaged kernels (IDK) per food-resource unit. For example, in the USA (HAGSTRUM, FLINN 1996) the following EITs are used to reject the commodity for human consumption: 32 IDK/100 g of grains (in mills 5 IDK/100 g) and 75 insect fragments/50 g of flour (in mills 15 insect fragments/50 g). It seems that farmers and store-keepers most frequently use the pest population density as the only qualitative criterion whereas food industry plants use additional qualitative and safety criterions in connection with the hazard analysis of the pest infestation. Thus we can recognise that various food-storing and producing subjects use various economic injury thresholds: EIT of present living pest (EIT_N), EIT of insect damage kernels (EIT_{IDK}) and EIT of filth (e.g., fragment, hairs, faeces) (EIT_F). Despite the use of various EITs in practice, there is surprisingly very little information on the relationship and its quantification among these EITs. It is apparent from Fig. 3 that the number of injured kernels EIT_{IDK} (≅ exploitation of the food resource [E] in our case) is not simply correlated with No. of present living pests EIT_N. Clearly, we would like to stress that the above mentioned critical thresholds (EIT_N, EIT_{IDK}, EIT_F) should be treated in some instances as independent food safety and qualitative criterions. Neglecting this fact by food grain suppliers (farmers, storekeepers, agro-traders), which rely mainly on "*N*"-monitoring, may result in a tricky situation when their customers (e.g., flour mill laboratory), using other EITs, label the grain load as a "low grade" or "not for human consumption" even though the supplier delivers grain without pest or under 2 living pests per kg of the commodity. To prevent this situation a zero pest population level should be maintained during the whole period of food commodity storage (which is not economical and "ecological") or a monitoring of all types of EITs should be established. The problem is that for entomicroanalysis, besides laboratory and microscopic equipment, some type of special entomological and chemical qualifications is needed. This could be solved by purchase of such analytical service from a district agricultural and advisory laboratory. We think that another and probably more operational approach could be an establishment of some form of the continual "cumulative monitoring", based on collection of cumulative capture data from traps during the whole storage of the particular batch of the commodity. Cumulative capture indices, although with certain bias, give certainly a better picture of the past infestation and commodity damage than discontinual sampling. I suppose that work by VELA-COIFIER *et al.* (1997), though proposing only week cumulative thresholds per insect trap, indicates that this approach could be feasible.

Conclusions

Unlike cumulative pest numbers the pest population density is not always consistent with injuries (e.g., weight losses or No. of injured kernels) of stored food product. HACCP and IPM programmes should therefore ensure not only monitoring of pest population density but also of the criterions directly reflecting the actual injury of food resource along the whole food production chain. It is suggested to initiate a research program studying the relationship between "cumulative trap-monitoring" of pests and the level of injury/contamination of stored food products. The research is also needed to improve some current methods of food entomological microanalysis, particularly in terms of detection and determination of stored product pest eggs.

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Souhrn

STEJSKAL V. (2000): **Nelineární vztah mezi exploatací potravního zdroje a aktuální populační hustotou skladištních škůdců.** Czech J. Food Sci., **18**: 81–85.

V práci jsou prezentovány dva konceptuální modely demonstrující nelinearitu aktuálních počtů skladištních škůdců k poškození potravních zdrojů. První model upozorňuje na zanedbávaný fakt, že kumulativní počty narůstají rychleji než aktuální počty, což vede k podhodnocení kritického počtu škůdců odpovídajícího reálnému prahu škodlivosti. Druhý model ukazuje, že aktuální populační hustota škodlivého organismu může odpovídat naprosto odlišnému stupni exploatace potravního zdroje (tj. poškození a ztrátám). V práci je upozorněno na význam kontinuálního monitorování pomocí sběru kumulativních dat z lapačů, které dokumentují historii populace škůdce na sledovaném potravním zdroji. Kromě sledování aktuálního počtu živých škůdců a „kumulativního monitorování" by mělo být nezbytou součástí programů HACCP a IPM v potravinářských zařízeních rovněž monitorování stupně poškození a kontaminace skladovaných produktů pomocí metod potravinářské mikroanalytické entomologie.

Klíčová slova: populační dynamika škůdců; prahy škodlivosti; rozhodovací procesy; HACCP

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