

The effect of stored barley cultivars, temperature and humidity on population increase of *Acarus siro*, *Lepidoglyphus destructor* and *Tyrophagus putrescentiae*

Jan Hubert · Stano Pekár · Radek Aulický ·
Marta Nesvorná · Václav Stejskal

Received: 13 July 2012 / Accepted: 20 November 2012 / Published online: 29 November 2012
© Springer Science+Business Media Dordrecht 2012

Abstract The rate of population increase of three mite species, *Acarus siro* (L.), *Lepidoglyphus destructor* (Schrank) and *Tyrophagus putrescentiae* (Schrank), was studied on various types of barley and at various combinations of temperature and humidity. The mites were added into the chambers and incubated for 21 days on seven different kinds of barley coming from four sites, including six cultivars and a mixture. The population increase of all species was higher on the mixture than on any other cultivar, except for Sebastian and Calgary. The increase of mites was studied at constant temperatures ranging from 5 to 35 °C and relative humidity (RH) ranging from 50 to 90 %. Positive rate of increase was found above 70 % RH for all species. The optimal humidity was at 85 % RH for *A. siro* and *L. destructor* and at 90 % RH for *T. putrescentiae*. As concerns the temperature, positive rate of increase was found at temperatures higher than 10, 15 and 20 °C for *A. siro*, *L. destructor* and *T. putrescentiae*, respectively. The temperature optima were at 23, 25, and 30 °C for *A. siro*, *L. destructor* and *T. putrescentiae*, respectively. Model estimated on laboratory data was then fitted to temperature and humidity records from August to November in the Czech grain store. Estimated population rate of increase was rarely positive: for *A. siro* it was for 24 %, for *L. destructor* for only 1 % and for *T. putrescentiae* for only 7 % days of the study period. It is concluded that in the climatic conditions of the Czech Republic the population increase of three mite pests is negligible during autumn and winter.

Keywords Mite · Temperature · Humidity · Population increase · Barley · Store

J. Hubert (✉) · R. Aulický ·
Marta Nesvorná · V. Stejskal
Crop Research Institute, Drnovská 507, 161 06 Prague 6, Czech Republic
e-mail: hubert@vurv.cz

S. Pekár
Department of Botany and Zoology, Masaryk University, Kotlářská 2,
61137 Brno, Czech Republic

Introduction

Mites are important pests of stored products (Hughes 1976). Mite contamination decreases the quality, germination and nutrient content of the stored grain (Armitage et al. 2002; White et al. 1979). Stored mites produce allergens causing respiratory disease and atopic dermatitis of farmers (Hage-Hamsten-van et al. 1988; Arlian et al. 1997; Colloff 2009). There are also reports of anaphylactic reaction in humans (Sanchez-Borges et al. 1997) and decrease of weight in pigs (Braude et al. 1980; Zdarkova and Horak 1993) after feeding mite contaminated food/feed. The mites feed on fungi producing mycotoxins and are vectors of the fungi through the grain (Hubert et al. 2004; Nesvorna et al. 2012). The arthropod feeding can modulate the mycotoxin production (Rohlf and Churchill 2011). The mites also interact with bacteria including some of human pathogen importance (Hubert et al. 2012).

These threats are believed to be serious when mite population density is high, for example, higher than 1,000 mites/kg of grain. Survey of the Czech grain stores, revealed that only 8 % of stores were infested by mites with densities higher than 1,000 individuals but most stores (57 %) were infested by lower densities, ranging from 1 to 1,000 mites/kg (Stejskal and Hubert 2008). To understand such large variation and predict occurrence of threats it is essential to study effect of all factors that influence the mite population density.

Generally, the levels of infestation is influenced by physical conditions of the environment, namely humidity, light and temperature (Barker 1967; Cunningham 1965; 1969; 1976; Solomon 1962; Stratil et al. 1980; Fields 1992); quality and quantity of resources (Sinha and Kawamoto 1990; Stejskal et al. 2003; Palyvos et al. 2008; Athanassiou et al. 2011); presence and abundance of enemies, such as predators and competitors; and presence of pesticide residues. In a recent paper Collins (2012) reviewed a number of factors that have been known to affect population growth of several mite species in stores and stressed very important role of physical conditions.

The prediction of mite population dynamic during season is essential for planning chemical or physical pest control that keeps mites below the economic threshold (Stejskal and Hubert 2008). Estimation of parameters for a predictive model has been based on two different approaches. Collins (2012) used field observations of seasonal mite population fluctuations and related them to the temperature and humidity conditions of the grain. Although direct observation of the mite population density provides real estimates, the sampling can be biased due to extraction method used, for example (Krizkova-Kudlikova et al. 2007; Hubert et al. 2009a). The other approach is based on the laboratory experiments of population increase under given constant physical conditions and resources (Cunningham 1976; Sanchez-Ramos and Castanera 2005; Sánchez-Ramos et al. 2007a, b). As the conditions and resources are not constant in the stores, but change during the storage period, a number of laboratory experiments at a variety of conditions are needed.

The previously constructed predictive models for mite population growth in the grain used temperature as the only predictor (Kawamoto et al. 1991; Pekar and Zdarkova 2004; Aspaly et al. 2007; Pekar and Hubert 2008). In this study our aim was to study effect of other two important variables, humidity and food type. We investigated the effect of six barley cultivars (and a mixture) coming from four harvesting sites on the population increase of three species of mites because previously we observed that cultivars can affect markedly population increase (Kucerovala and Stejskal 1994). We selected barley cultivars for our experiments as we found higher infestation level in the barley than in the wheat in the Czech grain stores (Hubert et al. 2009b). We measured population increase of three mite species for different combinations of potential temperature and humidity conditions.

Finally, we used constructed model to simulate population dynamics of the three species using actual storage conditions from a store in the Central Bohemia.

Materials and methods

Mites

The tested strains of *Acarus siro* (L.), *Lepidoglyphus destructor* (Schrank) and *Tyrophagus putrescentiae* (Schrank) originated from laboratory stock cultures kept at the Crop Research Institute, Prague, Czech Republic (CZ). *A. siro* and *T. putrescentiae* were collected from the grain mass stored in Buštěhrad, CZ in 1996 (E. Zdarkova). The mites have been reared on a mixture of oat flakes, wheat germ and dried yeasts (Pangamin, Rapeto, Bezdruzice, CZ) at a ratio 10:10:1 (w/w). *L. destructor* came from food a processing factory (CZ), collected in 1965 (E. Zdarkova). The mites have been reared on a mixture of dog food (Ontario-pet, Placek, Podebrady, CZ), wheat germ, dried fish food (LonBio, Aqua Tropic Lonsky, Praha, CZ), dried yeasts and gelatin (Serva Electrophoresis GmbH, Heidelberg, Germany) at a ratio 10:10:3:2:1 (w/w). All species of mites were kept in Iwaki cell tissue chambers (Cat. No. S401879.1, P-lab, Prague, CZ). The chambers were palced in the Secodar 4.0 boxes (Cat. No. A741000, P-Lab) with saturated KCl solution providing 75 % r.h. Before the experiment, the mites were collected from the surface of the tissue chambers by a camel-hair brush under a Stemi 2,000 C dissection microscope (C. Zeiss, Jena, Germany). Unsexed adults of undetermined age were used for the assays.

Barley cultivars

The barley cultivars were harvested in August 2008 in Central Bohemia and immediately after the harvest were transferred to Crop Research Institute. They were cleaned and stored at 5 °C for 1 month before start of the experiments. There were six barley cultivars harvested at four sites were used: Calgary (harvested at Trebiz), Diplom (harvested at Horovice and Klobouky), Jersey (harvested at Klobouky, Prague and Trebiz), Prestiz, Sebastian and Tolar (all harvested at Horovice). The mixture of undetermined cultivars (originating from the experimental field at Prague—Ruzyne) was obtained from the local grain store. Before the experiment, the barley was dried at 50 °C for 6 h and the dust fraction was removed by sieving at AS240 digit Retch sieving machine (Retch, de-Haan, Germany). The barley was remoistened by distilled water and the humidity was checked using an Agricomputer MK2 (Opting servis, Ostrava, CZ). To obtain appropriate moisture the barley was pre-incubated in plastic boxes with saturated KCl solution (cca 85 % r.h.). After preincubation the remoistened barley was weighted to 25 g (0.01 g accuracy) on Navigator microbalance (Ohaus, Pine Brook, NJ, USA) and placed into plastic IWAKI chambers (P-LAb, Prague, CZ).

Experimental design

The comparison of barely cultivars was tested in 10 replicates per each barley cultivar and each mite species. Ten specimens of each species were added separately into Iwaki chamber and incubated in Secador desiccators (P-Lab) in the darkness at 25 °C and 84 % r. h. The

chambers were incubated for 21 days. The experiment was terminated by the extraction of the mites in Tullgren-Berlese funnels. The mites were counted under a dissection microscope.

In another experiment designed to determine the effect of temperature and moisture (see Table 1) we used 6 replicates. The design was similar to the previous experiments, but the chambers were kept in desiccators using different salt solutions. The grain was a mixture of undetermined cultivars. The relative humidity ranged from 50 to 90 % and the temperature ranged from 5 to 35 °C. The length of experiment was 21 or 42 days (Table 1). The termination of experiment was similar as is described above.

Monitored temperature and moisture in field farm flat-store

Continuous measurements of temperature and moisture came from a flatfarm store in Trebiz (CZ). The stored barley was harvested in August 2009. The temperature and humidity was monitored from August to November 2009, when barley was emptied. The temperature and humidity was monitored using Tinytag Plus two Logger sensor (cat No. 4505, Omni-Instruments, Dundee, Scotland, UK) every 3 h. The sensor was situated 10 cm below the surface level of stored barley. From recorded data we estimated daily average of temperature and moisture and used it in the simulation model (see below).

Data analyses

The intrinsic rate of population increase (r) was estimated using the formula for exponential population growth ($N_t = N_0 e^{rt}$). This response variable showed homoscedastic variance and symmetrical distribution. The effect of harvesting site and barley cultivar on r was studied using Linear Mixed-effect Model (LME) (Pekar and Brabec 2012) in order to estimate variance components for the site and cultivar (cultivar nested within site). The fixed effects were composed of two explanatory variables, mite species and barley cultivar. The fit of the model was checked using diagnostic plots. Following LME, the effect of cultivar on r was studied separately for each mite species with one-way ANOVA, i.e. with a single factor. Tukey HSD test was used to compare the mean of rate among cultivars.

The response of mite density to the temperature and humidity gradient was studied using Generalized Additive Models (GAM) because the response was strongly non-linear

Table 1 Experimental conditions used for the observation of population increase of tested mites at different moisture and temperature combinations

Temperature [°C]	Duration of experiment	Relative humidity (%)				
		KCl	NaCl	NH ₄ Cl	NaNO ₃	Mg(NO ₃) ₂
5	42	87.7	75.7	80.6	71.1	58.9
10	42	86.8	75.7	80.6	75.1	57.4
15	21	86.8	75.7	79.9	76.0	55.9
20	21	85.1	75.7	79.2	73.2	54.4
25	21	84.3	75.3	78.6	74.5	52.9
30	21	83.6	75.1	77.2	70.4	51.4
35	21	83.0	74.9	77.0	69.7	49.9

The relative humidity of saturated salt solution is according to Eaton and Kells (2009); Aspaly et al. (2007)

(against both explanatory variables), and a satisfactory fit could not be obtained by using any non-linear temperature-dependent model (Kontodimas et al. 2004). The response was the intrinsic growth rate. Since r has symmetric unbounded distribution and homoscedastic variance Gaussian family and identity link were used (Wood 2006). The linear predictor was an interaction between temperature and relative humidity. It was modelled using thin-plate regression splines. The basis dimension of the spline was set at default, which provided fit higher than 90 % (R^2 adjusted).

Estimated model for each mite species (on mixture of barley cultivars) was then used to predict rate of population increase for data on temperature and humidity obtained from a grain store at Trebiz. All analyses were performed within the R environment (R Development Core Team 2011).

Results

The effect of barley

Estimation of variance components revealed that the site explained negligible variation in the data ($\sigma^2 = 1.7 \times 10^{-11}$), whereas cultivar explained 54 % ($\sigma^2 = 1.9 \times 10^{-3}$). The interaction between mite species and cultivar on r was highly significant (LME, $F_{12,264} = 5.3$, $P < 0.0001$) showing that the cultivar had different effect on the population increase of the three mite species (Table 2). For *A. siro* the effect of cultivar was highly significant (ANOVA, $F_{9,86} = 19.8$, $P < 0.0001$): the rate was significantly lower on Diplom and Jersey in comparison with the mixture and Sebastian in particular (Table 2). For *L. destructor* the effect of cultivar was also highly significant (ANOVA, $F_{9,86} = 21.7$, $P < 0.0001$): the rate was significantly lower on all cultivars in comparison with the mixture, Calgary and Sebastian (Table 2). For *T. putrescentiae* the effect of cultivar was also highly significant (ANOVA, $F_{9,86} = 24.6$, $P < 0.0001$): the rate was significantly lower on all cultivars in comparison with the mixture and on Sebastian (Table 2).

The effect of temperature and humidity

The obtained data are summarized in Table 3. For *A. siro* the effect of temperature and humidity on the rate was significant (GAM, $F_{28} = 115.4$, $P < 0.0001$, $R^2_{\text{adj.}} = 0.93$) and

Table 2 Observed mean rate of population increase (SE) for the three mite species reared on six barley cultivars and a mixture of barley cultivars

Cultivar	<i>Acarus siro</i>	<i>Lepidoglyphus destructor</i>	<i>Tyrophagus putrescentiae</i>
Mixture	0.16 (0.007) ^a	0.13 (0.004) ^a	0.16 (0.004) ^a
Calgary	0.10 (0.006) ^{ab}	0.10 (0.006) ^a	0.12 (0.006) ^b
Diplom	0.09 (0.009) ^b	0.02 (0.009) ^b	0.08 (0.005) ^c
Jersey	0.03 (0.015) ^c	0.02 (0.008) ^b	0.08 (0.004) ^c
Prestiz	0.10 (0.006) ^a	0.03 (0.015) ^b	0.07 (0.010) ^c
Sebastian	0.15 (0.007) ^a	0.11 (0.015) ^a	0.17 (0.006) ^a
Tolar	0.12 (0.006) ^a	−0.01 (0.006) ^b	0.09 (0.007) ^b

Tukey HSD test was used to compare the rate among cultivars. Different superscript letters identify significant difference (at $\alpha = 0.05$)

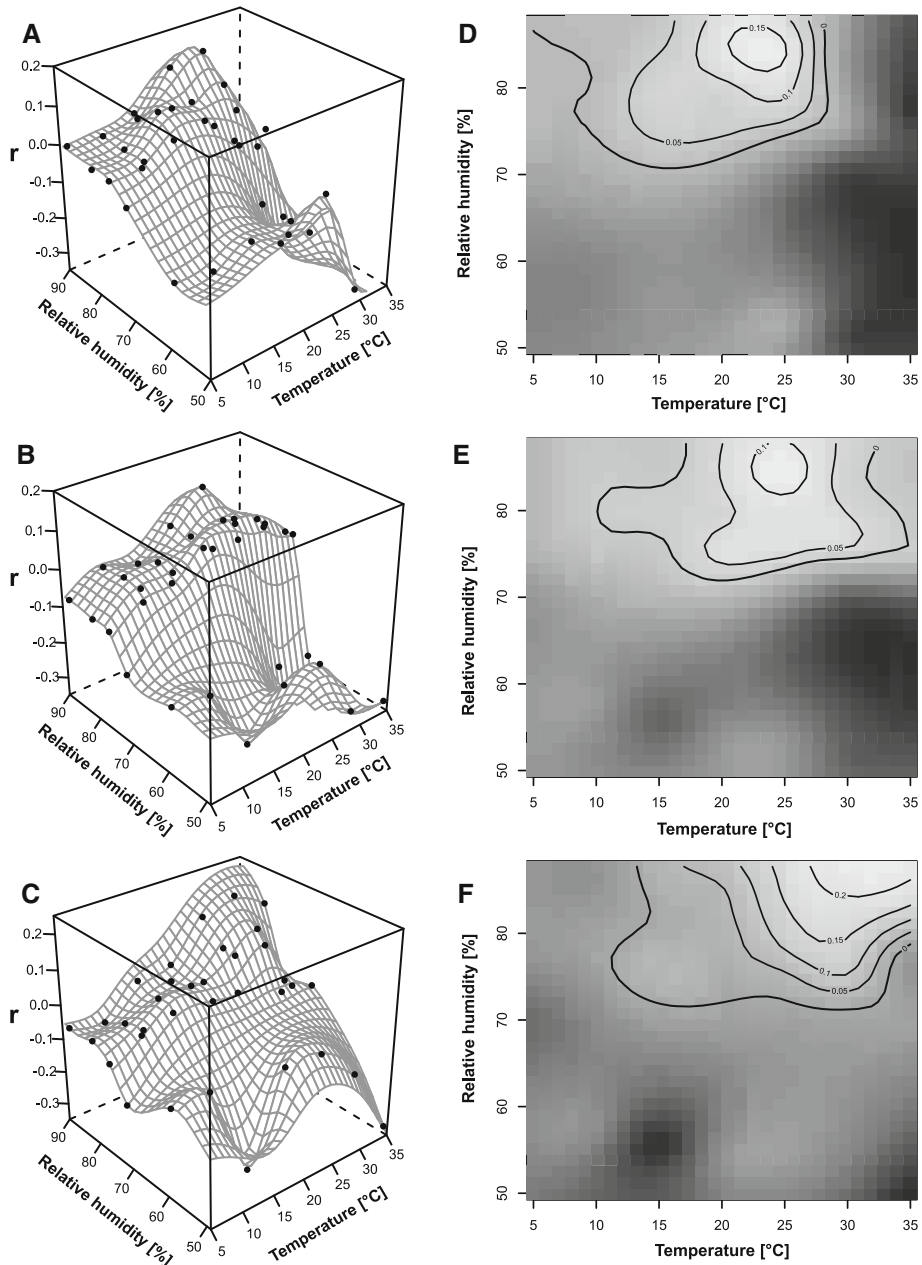


Fig. 1 Surface (a–c) and contour (d–f) plots of intrinsic growth rate (r) when related to relative humidity and temperature. The surface and contours were estimated using GAM. In the surface plots the points are means. In the contours plots only contours for positive values are displayed. The thick isocline is 0. **a, d.** *Acarus siro*; **b, e.** *Lepidoglyphus destructor*; **c, f.** *Tyrophagus putrescentiae*

non-linear (Fig. 1a). Positive growth rate of mites was approximately above 70 % r.h. and 10 °C (Fig. 1d). The maximum rate was estimated at 23 °C and 85 % r.h. For *L. destructor* the effect of temperature and humidity on the rate was also significant (GAM,

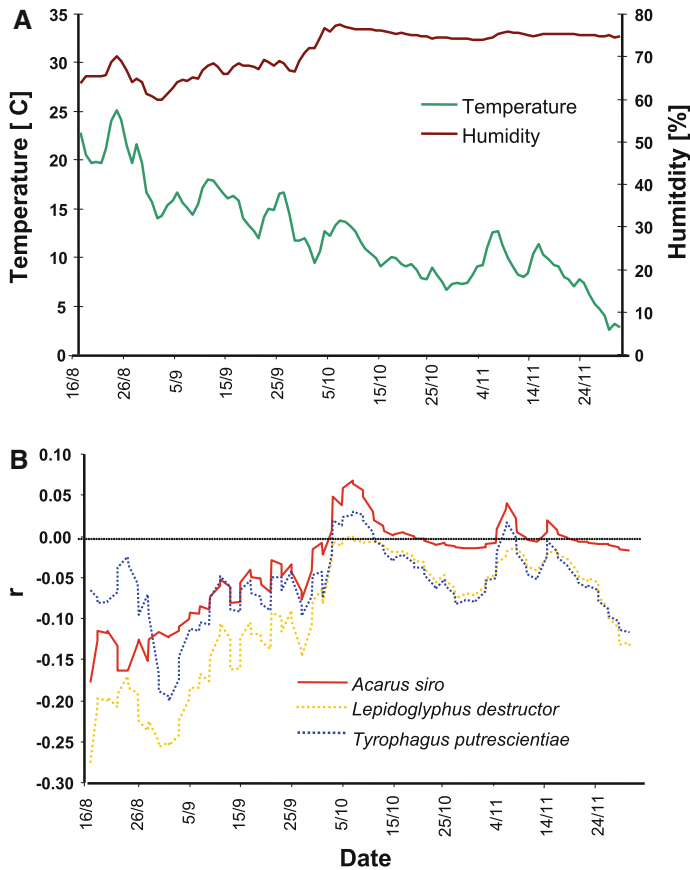


Fig. 2 The simulation of the growth of mites in Trebiz grain stores. **a** Change in the mean day temperature and humidity during 107 days from August to November. **b** Predicted rate of population increase for three mite species using GAM models

$F_{28,2} = 145.4$, $P < 0.0001$, $R_{adj..}^2 = 0.95$) and non-linear (Fig. 1b). Positive growth rate was found above 70 % r.h. and 15 °C (Fig. 1e). The maximum rate was at 25 °C and 85 % r.h. For *T. putrescentiae* the effect of temperature and humidity on the rate was significant (GAM, $F_{28,1} = 82.6$, $P < 0.0001$, $R_{adj..}^2 = 0.90$) and non-linear (Fig. 1c). Positive growth rate was found above 70 % r.h. and 20 °C (Fig. 1f). The maximum rate for *T. putrescentiae* was at 30 °C and 90 % r.h.

Simulation of the growth rate of mites

In the grain store the temperature decreased (with fluctuations) from 25 to 3 °C and the humidity increased from 60 to 75 % from August to November (Fig. 2a). The estimated population rate of increase was rarely above zero: for *A. siro* it was for 24 % ($N = 107$ days), for *L. destructor* for only 1 % and for *T. putrescentiae* for only 7 % days of the study period (Fig. 2b). However, even the positive values were lower than 0.07, thus, simulated increase in population density was very low.

Discussion

All three tested explanatory variables, i.e. barley cultivar, temperature and humidity, strongly influenced rate of population increase of *A. siro*, *L. destructor* and *T. putrescentiae*. Thus a predictive model should include at least all these variables to achieve a reasonable predictive power.

The quality of the grain was known to have strong effect on the population increase of mites (Collins 2012). The quality includes the nutritional content and the condition of the grain. Grain in a good condition, unbroken and clean, is less attacked by mites than damaged and dusty grain (Solomon 1969). In this study the condition of grain quality was standardized as a result of drying, moisturizing, sieving, thus removing the fine materials, which is critical for development of some mite species (e.g., *L. destructor*). Therefore, the effect of site was negligible.

The barley cultivars differ in nutritional content. The effect of cultivar on the rate of population increase has not been investigated before, yet nutritional content of the grain can affect the population increase. Recently Nietupski and Ciepielewska (2006) found different population increase of *A. siro* on a number of barley cultivars. In their study the population increase was positively related to the malting quality of barley grain and negatively to its protein content. Interestingly, the highest rate in our study was observed on the mixture of cultivars. So the mixture seems to provide optimal resource quality to all three mite species. The still open question is the high variability among the cultivars and the higher growth of mites on the cultivar mixture. However, the practice is that the barley cultivars are mixed according to the contract between farmer and purchaser. It means that the cultivars are not stored separately but in the mixture.

The population strains, wild and laboratory reared, may differ dramatically in fitness components (Fields 1992). Wolska (1980) points out that inbreeding reduced fitness in laboratory populations. This would mean that rate of population increase obtained from laboratory reared strains is underestimated when compared to strains from the field. There is evidence that the field and laboratory strains differ in their sensitivity to pesticides, e.g. *Oligonychus pratensis* (Banks) to bifenthrin (Bynum and Archer 2002). In our study we used strains that were held in the laboratory for more than 15 years.

The comparison of previously published estimates for lower temperature thresholds is, however, complicated by the fact that different humidity was used. Solomon (1969) found the lower temperature threshold for *A. siro* to be 5 °C at 75 % r.h., while recently Aspaly et al. (2007) found it to be 10 °C at 85 % r.h.. This roughly corresponds to an estimate in this study. Stratil et al. (1980) observed positive growth rate at 15 °C and 70 % RH for *L. destructor*, which is similar to our estimation. But estimation of the lower temperature threshold for *T. putrescentiae* is different from previous studies. While previously 10 °C at 85 % r.h. was reported to be the lower threshold (Sanchez-Ramos and Castanera 2005; Aspaly et al. 2007), now we found it to be at 20 °C and 70 % RH.

Observed population rate of increase is rather similar to the rates observed in previous studies. The optimal values for population increase correspond to the previous observation. For *A. siro* it was at 20–25 °C and 85 % RH (Solomon 1969; Aspaly et al. 2007); for *L. destructor* it was at 25 °C and 85 % RH (Stratil et al. 1980; Danielsen et al. 2004); and for *T. putrescentiae* it was at 30 °C and 90–95 % RH (Sanchez-Ramos and Castanera 2005). Results from this study show that *A. siro* is better adapted to lower temperatures than *L. destructor* and *T. putrescentiae* irrespective of the tested barley cultivar. Of the latter two *T. putrescentiae* showed preference for higher temperatures and higher relative humidity.

The practical impact of constructed model is that a store did not provide opportunity for a massive growth of mites during autumn as favourable conditions were limited to a few days in October and November. Nevertheless, we have observed massive infestation of stored barley by all three mite species in other stores (Hubert et al. 2009b). This contradiction can be explained by a number of factors, which are reviewed by Collins (2012). In the study we demonstrated variability in growth rate of mites on different barley cultivars or sampled sites. For *A. siro*, the temperature models were sensitive to the diet, when higher growth rate was on laboratory rearing diet than on the wheat (Aspaly et al. 2007; Pekar and Hubert 2008). In our simulation the initial numbers of mite were low in order to simulate empty and clean store. However the mites showed density dependent population growth (Pekar and Hubert 2008). The physical conditions vary among years and within stores. Even when outdoor conditions are unfavourable, mites aggregate in hot spots, where they can develop more quickly due to the high temperature and moisture (Jian and Jayas 2012).

In order to improve the predictive model it is necessary to record physical conditions during the entire storing period at a variety of locations that differ in climatic conditions. Furthermore, it is essential to know distribution of temperature and RH in the column of a stored grain. Additionally, other variables which decrease mite population density could be considered to be included in the model. Such is the effect of predatory mites (*Cheyletus eruditus*, *C. malaccensis*) as it can affect the population density of pests dramatically (Pulpan and Verner 1965); the density-dependence; and the effect of pesticide residues (Collins 2006).

Acknowledgments The work was supported by two projects provided by the Ministry of Education, Youth and Sports of the Czech Republic: VS and RA were supported by KONTAKT II no. LH12160; MN by No. 0002700604, JH by NPII 2B08049. The authors wish to thank two anonymous referees for valuable comments and Pavel Horak for his excellent technical assistance during the experiments.

References

- Arlian LG, Vyszynski-Moher DL, Johansson SG, van-Hage-Hamsten M (1997) Allergenic characterization of *Tyrophagus putrescentiae* using sera from occupationally exposed farmers. *Ann Asthma Immunol* 79:525–529
- Armitage DM, Cook DA, Baxter DE (2002) Farm-scale experiments to compare infestation and quality changes in malting barley stored at three moisture contents. *J Inst Brewery* 108:178–186
- Aspaly G, Stejskal V, Pekar S, Hubert J (2007) Temperature-dependant population growth of three species of stored product mites (Acari: Acaridida). *Exp Appl Acarol* 42:37–46
- Athanassiou CG, Kavallieratos NG, Sciarretta A, Palyvos NE, Trematerra P (2011) Spatial associations of insects and mites in stored wheat. *J Econ Entomol* 104:1752–1764
- Barker PS (1967) The effects of high humidity and different temperatures on the biology of *Tyrophagus putrescentiae* (Schrank) (Acarina: Tyroglyphidae). *Can J Zool* 45:91–96
- Braude R, Low AG, Mitchell KG, Pittman RJ, Wilkin DR (1980) Effect of flour mite infestation (*Acarus siro* L.) on nutritive value of pig diets. *J Vet Rec* 106:35–36
- Bynum ED Jr, Archer TL (2002) Susceptibility of populations of Banks grass mites (Acari: Tetranychidae) suspected of developing bifenthrin resistance from three maize fields. *Exp Appl Acarol* 27:303–312
- Collins DA (2006) A review of alternatives to organophosphorus compounds for the control of storage mites. *J Stored Prod Res* 42:395–426
- Collins DA (2012) A review on the factors affecting mite growth in stored grain commodities. *Exp Appl Acarol* 56:191–208
- Colloff MJ (2009) Dust mites. CSIRO and Springer publishing, Dordrecht, The Netherlands
- Cunnington AM (1965) Physical limits for complete development of the grain mite *Acarus siro* (Acarina, Acaridae), in relation to its world distribution. *J Appl Ecol* 2:295–306

- Cunnington AM (1969) Physical limits for complete development of the copra mite, *Tyrophagus putrescentiae* (Schränk) (Acarina: Acaridae). In: Evans GO (ed) Proceedings of 2nd international congress of acarology 1967 Budapest, pp 241–248
- Cunnington AM (1976) The effect of physical conditions on the development and increase of some important storage mites. *Ann Appl Biol* 82:175–201
- Danielsen C, Hansen LS, Nachman G, Herling C (2004) The influence of temperature and relative humidity on the development of *Lepidoglyphus destructor* (Acari: Glycyphagidae) and its production of allergens: a laboratory experiment. *Exp Appl Acarol* 32:151–170
- Eaton M, Kells SA (2009) Use of vapor pressure deficit to predict humidity and temperature effects on the mortality of mold mites, *Tyrophagus putrescentiae*. *Exp Appl Acarol* 47:201–213
- Fields PG (1992) The control of stored-products insects and mites with extreme temperatures. *J Stored Prod Res* 28:89–118
- Hage-Hamsten-van M, Ihre E, Zetterström O, Johansson SG (1988) Bronchial provocation studies in farmers with positive RAST to the storage mite *Lepidoglyphus destructor*. *Allergy* 43:545–551
- Hubert J, Stejskal V, Munzbergova Z, Kubatova A, Vanova M, Zdarkova E (2004) Mites and fungi in heavily infested stores in the Czech Republic. *J Econ Entomol* 9:2144–2153
- Hubert J, Nesvorna M, Stejskal V (2009a) The efficacy of sieving, filth flotation and Tullgren heat extraction for detecting various developmental stages of *Tribolium castaneum* and *Ephestia kuehniella* in samples of wheat grain, flour and semolina. *J Stored Prod Res* 45:279–288
- Hubert J, Kucerova Z, Aulicky R, Nesvorna M, Stejskal V (2009b) Differential levels of mite infestation of wheat and barley in Czech grain stores. *Insect Sci* 16:255–262
- Hubert J, Kopecky J, Perotti MA, Nesvorna M, Braig HR, Sagova-Mareckova M, Macovei L, Zurek L (2012) Detection and identification of species-specific bacteria associated with synanthropic mites. *Microb Ecol* 63:919–928
- Hughes AM (1976) The mites of stored food and houses. Ministry of Agriculture Fishery and Food, London, p 400
- Jian F, Jayas DS (2012) Ecosystem Approach to Grain Storage. *Agric Res* 1:148–156
- Kawamoto H, Sinha RN, Muir WE, Woods SM (1991) Simulation model of *Acarus siro* (Acari: Acaridae) in stored wheat. *Env Entomol* 20:1381–1386
- Kontodimas DC, Eliopoulos PA, Stathas GJ, Economou LP (2004) Comparative temperature-dependent development of *Nephus includens* (Kirsch) and *Nephus bisignatus* (Boheman) (Coleoptera: Coccinellidae) preying on *Planococcus citri* (Risso) (Homoptera: Pseudococcidae): evaluation of a linear and various nonlinear models using specific criteria. *Env Entomol* 33:1–11
- Krizekova-Kudlikova I, Stejskal V, Hubert J (2007) Comparison of detection methods for *Acarus siro* (Acari: Acaridida: Acarididae) contamination in grain. *J Econom Entomol* 100:1928–1937
- Kucerova Z, Stejskal V (1994) Susceptibility of wheat cultivars to postharvest losses caused by *Sitophilus granarius* (L.) (Coleoptera: Curculionidae). *J Plant Dis Prot* 101:641–648
- Nesvorna M, Gabrielova L, Hubert J (2012) *Tyrophagus putrescentiae* is able to graze and develop on *Fusarium* fungi of mycotoxins importance under laboratory conditions. *J Stored Prod Res* 48:37–45
- Nietupski M, Ciepielewska D (2006) Correlation between malting quality of barley cultivars and development of flour mite (*Acarus siro* L.). *Pol J Nat Sci* 21:543–551
- Palyvos NE, Emmanouel NG, Saitanis CJ (2008) Mites associated with stored products in Greece. *Exp Appl Acarol* 44:213–226
- Pekar S, Brabec M (2012) Modern analysis of biological data. 2. Linear Models with correlation in R. Masaryk University Press, Brno. [in Czech]
- Pekar S, Hubert J (2008) Assessing biological control of *Acarus siro* by *Cheyletus malaccensis* under laboratory conditions: effect of temperatures and prey density. *J Stored Prod Res* 44:335–340
- Pekar S, Zdarkova E (2004) A model of the biological control of *Acarus siro* by *Cheyletus eruditus* (Acari: Acaridae, Cheyletidae) on grain. *J Pest Sci* 77:1–10
- Pulpan J, Verner PH (1965) Control of tyroglyphoid mites in stored grain by the predatory mite *Cheyletus eruditus* (Schränk). *Can J Zool* 43:417–432
- Rohlf S, Churchill ACL (2011) Fungal secondary metabolites as modulators of interactions with insects and other arthropods. *Fungal Gen Biol* 48:23–34
- R Development Core Team (2011) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available from <http://www.R-project.org/>
- Sanchez-Borges M, Capriles-Hulett A, Fernandez-Caldas E, Suarez-Chacon R, Caballero F, Castillo S, Sotillo E (1997) Mite-contaminated foods as a cause of anaphylaxis. *J Allergy Clin Immunol* 99(6 Pt 1):738–743
- Sanchez-Ramos I, Castanera P (2005) Effect of temperature on reproductive parameters and longevity of *Tyrophagus putrescentiae* (Acari: Acaridae). *Exp Appl Acarol* 36:93–105

- Sánchez-Ramos I, Alvarez-Alfageme F, Castañera P (2007a) Reproduction, longevity and life table parameters of *Tyrophagus neiswanderi* (Acari: acaridae) at constant temperatures. *Exp Appl Acarol* 43:213–226
- Sánchez-Ramos I, Alvarez-Alfageme F, Castañera P (2007b) Effects of relative humidity on development, fecundity and survival of three storage mites. *Exp Appl Acarol* 41:87–100
- Sinha RN, Kawamoto H (1990) Dynamics and distribution patterns of acarine populations in stored-oat ecosystems. *Res Pop Ecol* 32:33–46
- Solomon ME (1962) Ecology of the flour mite, *Acarus siro* L. (= *Tyroglyphus farinae* DeG). *Ann Appl Biol* 50:178–184
- Solomon ME (1969) Establishment, growth and decline of populations of the grain mite *Acarus siro* L. on a handful of wheat. In: Evans G O (ed) Proceedings of the 2nd International Congress of Acarology, July 1967, Sutton Bonington. Akademiai Kiado, Budapest, Hungary, 255–260
- Stejskal V, Hubert J (2008) Risk of occupational allergy to stored grain arthropods and false pest-risk perception in Czech grain stores. *Ann Agric Env Med* 15:29–35
- Stejskal V, Hubert J, Kucerova Z, Munzbergova Z, Lukas J, Zdarkova E (2003) The influence of type of storage on pest infestation of stored grain in the Czech Republic. *Plant Soil Environ* 49:55–62
- Stratil HU, Stratil HH, Knulle W (1980) Untersuchungen über die spezifische vermehrungsrate von populationen der im lagergetreide lebenden milbe *Glycyphagus destructor* (Schränk, 1781) bei verschiedenen Temperatur- und Luftfeuchtebedingungen. [Investigations on the specific increase rate of populations of the stored-grain mite *Glycyphagus destructor* (Schränk, 1781) under various temperature and air humidity conditions]. *Zeitschrift für Angewandte Entomologie* 90:209–220
- White NDG, Henderson LP, Sinha RN (1979) Effects of infestations by three stored-product mites on fat acidity, seed germination, and microflora of stored wheat. *J Econ Entomol* 72:763–766
- Wolska KJ (1980) Effect of inbreeding on quantitative features of copra mite *Tyrophagus putrescentiae* Schr. *Acarina: Acaridae. Genet Polonica* 21:291–307
- Wood SN (2006) Generalized Additive Models: An Introduction with R. Chapman and Hall/CRC
- Zdarkova E, Horak E (1993) The effects of diets with mites (*Acarus siro* L. : Acaridae) on the performance and carcass quality of pigs. *Zeitschrift für angewandte Zool* 79(1):117–126