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Prediction of insect development in a wheat (*Triticum aestivum*) silo-bag by computer simulation

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ABSTRACT

Population growth rates for two insect species, viz. *Rhyzopertha dominica* (Fabricius) and *Sitophilus oryzae* (L.), predicted by Driscoll and others, was coupled with a silo bag heat and mass transfer model earlier validated for wheat (*Triticum aestivum* L.). The rate of population increase per week was evaluated as a function of the grain temperature and intergranular relative humidity during storage from summer to winter of dry wheat (13% w.b. and 25°C initial temperature). The wheat was produced in areas with sub-tropical, intermediate and moderate weather conditions. Results showed that the feasibility of insect control by effect of temperature was rather weak for the Central and Southern regions of Argentina, while the rate of population increase per week remained above the unit for the sub-tropical region. To account for the effect of oxygen (O_2) intergranular concentration on the rate of population increase per week, a very simplified correction factor was proposed to modify Driscoll's model. Population increase was re-calculated for *Rhyzopertha dominica* with an initial adult insect infestation of 0.1 and 1 insect/kg. Evolution of insect population, gas concentration, and grain dry matter loss were predicted considering a gas ingress rate of 0.05%– 0.22% O_2/d. With 1 insect/kg initial infestation, an atmosphere composition favourable to arrest insect activity was achieved with O_2 concentration ranging from 2 to 5%V/V.

Key words: Atmosphere composition, Grain storage, Hermetic storage, Modeling, Silo-bags, Wheat

When grain is stored in an airtight system, respiration of insects increases the rate at which intergranular O_2 is consumed and carbon dioxide (CO_2) is produced, which in turn affects the rate of insect development. Navarro et al. (1994) described a model to simulate the changes in gas concentrations, insect populations and amounts of grain consumed. To the best of the author's knowledge, work of Navarro et al. (1994) is the only published text that accounted for the interdependent changes in gas concentrations and dynamics of insect populations under hermetic storage. Most of the predictive insect population models were coupled to heat and mass transfer models, to evaluate aeration strategies as a tool for controlling insect pests (Throne, 1995; Thorpe, 1997; Montross, 1999; Driscoll et al., 2000) or to analyze the development of hot spots in conventional storage bins (Mani et al., 2001) and did not consider the effect of intergranular gas composition.

Arias Barreto et al. (2013) analyzed wheat (*Triticum aestivum* L.) storage conditions in a silo bag under a sub-tropical climate (Sáenz Peña, Chaco Province), an intermediate climate (Pergamino, Buenos Aires Province) and temperate climate (Balcarce, Buenos Aires Province). Based on the change of wheat temperature during storage, it was concluded that for the Central and Southern regions of Argentina, insect activity would be limited for dry and moist wheat because the mean temperature of grain decreases below 17°C during autumn and winter, preventing insect population development. When wheat is stored at 14% w.b. or 16% w.b., insect activity is limited as result of low O_2 and high CO_2 concentration in the silo bag. When storing dry wheat (e.g. 12% w.b.) insect

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populations could develop during summer and early autumn (or during the entire year in regions with sub-tropical weather) because neither temperature nor O_2 and CO_2 concentration would be limiting.

It is important to note that in Argentina, the presence of stored-product pests in the field is uncommon, so the possibility of bagging infested wheat is low. Grain is harvested, transferred into a wagon and bagged in the same operation. An additional advantage of the silo bags is that the new plastic bag is insect free, and the plastic cover acts as a physical barrier, so if grain comes from the field free of insects, no further infestation should occur during storage.

The aim of this study is to link the insect population model developed by Driscoll et al. (2000) to the silo bag model developed by Arias Barreto et al. (2013) in order to predict the insect development in a silo bag. An infested silo bag scenario was simulated to quantify the effect of temperature on insect population development.

The rate of population increase per week of the predominant pests, *Rhyzopertha dominica* (Fabricius) and *Sitophilus oryzae* (L)*,* was evaluated as a function of the grain temperature and intergranular relative humidity during storage from summer to winter of dry wheat (12% w.b. and 25°C initial temperature) in the three regions of Argentina mentioned previously.

Arias Barreto et al. (2013) predicted the evolution of O_2 and CO_2 concentrations in a silo bag holding dry wheat without insect infestation and without any structural damage (reference case). The study analyzed how the presence of insects would modify this evolution and estimated the initial insect populations that could reduce O_2 concentration hostile to insect activity. To account for the influence O_2 intergranular concentration created on the rate of population increase per week, a simple correction factor was proposed to modify Driscoll's model. Population increase was re-calculated for *Rhyzopertha dominica,* under the moderate climatic conditions of the Balcarce area. Insect respiration rate was modeled as function of O_2 production according to Emecki et al. (2001). Evolution of insect population, gas concentration, and grain dry matter loss (DML) were predicted. A damaged silo bag was modeled assuming different O_2 ingress rate per day.

MATERIALS AND METHODS

Mathematical modelling

Silo bag heat and mass transfer model: Stating the energy and mass balances for the grain and air phases in a control volume, a coupled system in terms of temperature (*T*), grain moisture content (*W*), oxygen (O_2) and carbon dioxide (CO_2) concentrations were derived. The balances take into account heat, water vapour, O_2 consumed and CO_2 released by respiration of the grain ecosystem, which is modeled according to White's et al. (1982) correlation. A detailed description of the model is presented elsewhere (Gastón et al., 2009; Abalone et al., 2011a, b; Arias Barreto et al., 2013).

Insect population model: Insect population in grain storage was predicted according to Driscoll et al. (2000) as follow:

$$N(t+\Delta t) = N(t)e^{r_m \Delta t} = N(t)\lambda \quad (1)$$

$$\frac{dN(t)}{dt} = N_0 r_m e^{r_m t} \quad (2)$$

$$r_m = f'(RH)e^{k_1 T} + \ln\left[k_2\left(T_m - T\right)\right] \text{ with}$$

$$f'(RH) = k_a + k_b RH + k_c RH^2 \quad (3)$$

where *N* is the number of insects, N_0 is initial adult insect infestation, r_m is the intrinsic rate of increase, *t* is time in weeks, *RH* is intergranular relative humidity (decimal), *T* is temperature in °C, k_1, k_2, k_a, k_b, k_c are coefficients of growth model rate, T_m is a mortality temperature limiting population growth at temperatures near T_m, $\Delta t = 1$ week, λ, dimensionless, is the population increase per week. Coefficient of growth model rate *k* and T_m depend on insect species [*Rhyzopertha dominica, Sitophilus oryzae, Oryzaephilus surinamensis* (L.)*, Tribolium castaneum* (Herbst)].

According to Driscoll, the model is an indicator of the probability of insect infestation, not a prediction of actual insect numbers. Fig. 1 shows λ as function of temperature for 70% and Fig. 2, the dependence of factor *f'(RH)* with r.h. When temperature is close to T_m, λ falls sharply below 1, making insect population decrease to zero very fast. Depending on species, insect population will start to decrease at a lower rate when temperature is 11°C for *Rhyzopertha dominica,* 12°C for *Sitophilus oryzae,* 15.5°C for *Oryzaephilus surinamensis,* and 16°C for *Tribolium castaneum*. For *Sitophilus oryzae, Oryzaephilus surinamensis* and *Tribolium castaneum,* λ decreases with relative humidity while the opposite behaviuor was observed for *Rhyzopertha dominica*.

Effect of O_2 concentration

The interrelation between factors affecting insect mortality in hermetic storage is very complex (Navarro, 2006) and to take into account such factors in a simulation model is not a simple task. In a first

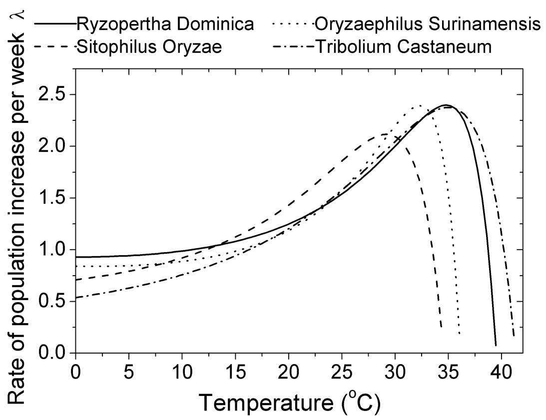

Fig. 1. Rate of population increase per week (λ) Driscoll et al. (2000); r.h.=70%

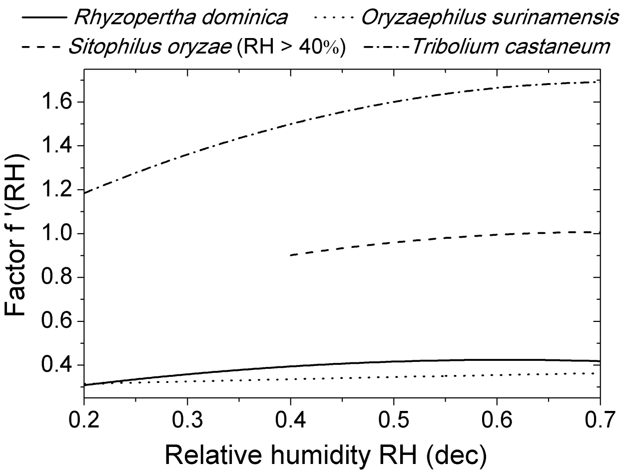

Fig. 2. Factor f '(RH) vs relative humidity (Driscoll et al., 2000)

attempt, a simple correction factor was proposed to include the effect of O_2 on insect population dynamics:

$$r_c\left(RH,T,O_2\right)=\left(f'\left(RH\right)e^{k_1T}+\ln\left[k_2\left(T_m-T\right)\right]\right)g\left(O_2\ \right) \quad ...(4)$$

The factor g (O_2) assumed that when O_2 level was equal or greater than 10% V/V, λ was given by Eq.(3), that is to say insect activity would be limited by effect of temperature. When O_2 level was around 5% V/V, λ was close to 1, which means that population growth would start to be arrested. Near 3% V/V O_2, an average rate per week value of 0.5 was proposed, though the rate of mortality is strongly dependent on developmental stage and age of species. By use of the proposed factor to model the effect of O_2 it was possible to reproduce Navarro et al. (1994) simulations as shown in Appendix 1.

The effect of CO_2 concentrations were not considered. The gas levels achieved in silo bags holding wheat (Arias Barreto et al., 2013) are below 20% V/V and would not limit insect activity.

RESULTS AND DISCUSSION

Effect of temperature change during storage on insect population development

To estimate the effect of temperature as a controlling factor to insect development, λ was calculated according to the temperature change during storage, shown in Fig. 3 (surface, middle and average wheat temperature in the silo bag, Arias Barreto et al., 2013). Intergranular relative humidity was predicted by use of Modified Henderson Thompson Isotherm.

Infestation in a silo bag is not common and data to provide an estimate of initial insect density are lacking. Initial adult insect infestation was set to 1 insect/kg to provide a relative comparison of the temperature effect on species development. Figs. 4 and 6 show the rate of population increase per week, λ, for *Rhyzopertha dominica* and *Sitophilus oryzae,* respectively. These results show that under temperate and intermediate climate (Balcarce and Pergamino areas), the effect of temperature as a limiting factor is not strong but is

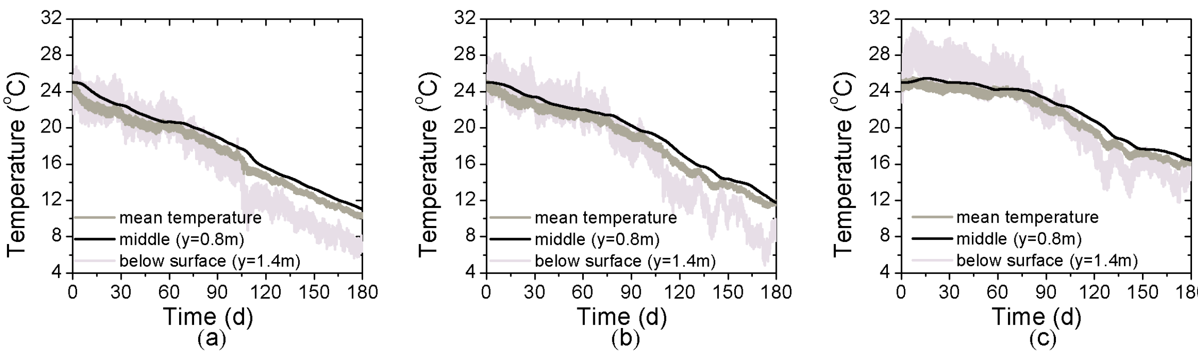

Fig. 3. Wheat temperature evolution at Balcarce (*a*), Pergamino (*b*) and Sáenz Peña (*c*). Initial temperature: 25ºC. Initial m.c. : 12% w.b, mean temperature; middle (y = 0.8 m); below surface (y = 1.4 m)

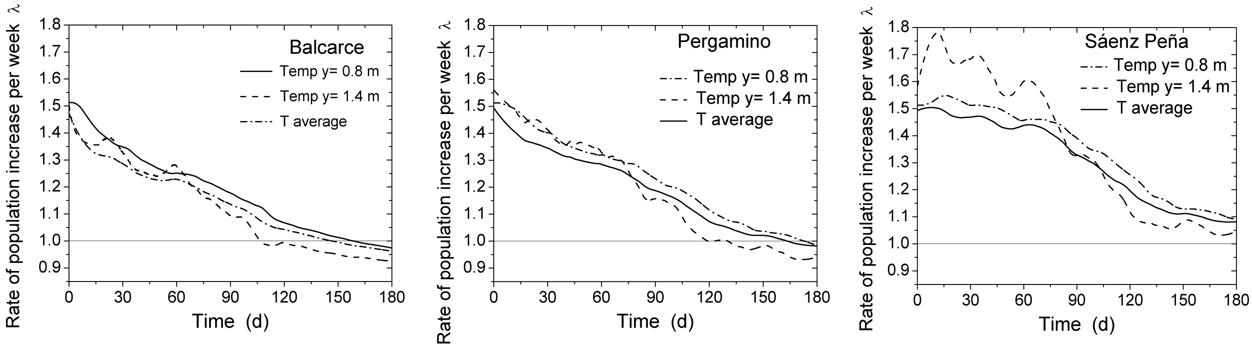

Fig. 4. Evolution of rate of population increase per week λ for *Rhyzopertha dominica* at Balcarce, Pergamino and Sáenz Peña. Bagging conditions: wheat at 25ºC, 12% w.b

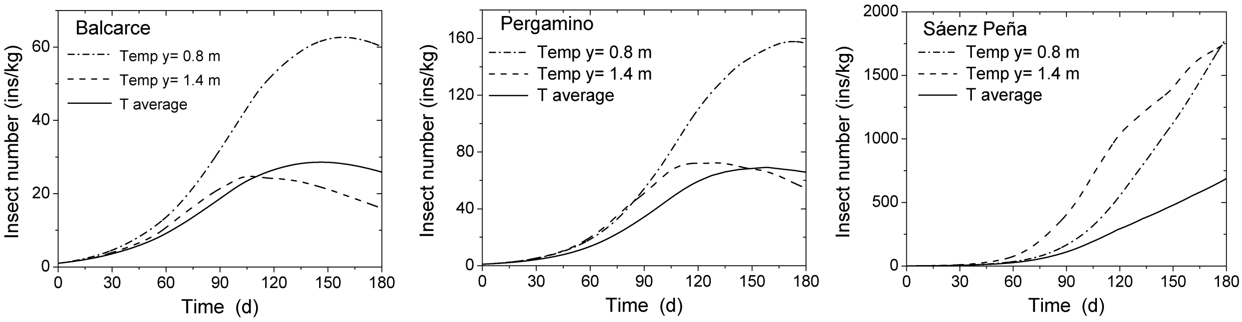

Fig. 5. Evolution of insect population for *Rhyzopertha dominica* at Balcarce, Pergamino and Sáenz Peña. Bagging conditions: wheat at 25ºC, 12% w.b.

slightly higher at the surface, because grain temperature decays to below 11°C and 12°C during the last two months of storage (winter). On an average, λ decreased below unit after 90 days of storage. At Sáenz Peña, with subtropical climate, predictions from previous work (Arias Barreto et al., 2013) are confirmed, as λ remained always above unit for both species.

Figs. 5 and 7 show the predicted evolution of insect population for *Rhyzopertha dominica* and *Sitophilus oryzae,* respectively. For *Rhyzopertha dominica,* at the surface layer, after the maximum value was attained the number of insects would reduce by 36% in Balcarce and 28% in Pergamino. For *Sitophilus oryzae,* the number of insect would reduce by 87% in Balcarce and 78% in Pergamino.

Effect of O_2 change during storage on insect population development

The model was run to predict the evolution of O_2 and CO_2 concentrations in a silo bag holding dry wheat (12% w.b.), in response to initial insect populations of 0.1 and 1 insect/kg (*Rhyzopertha dominica)* and gas ingress rate of 0.05% and 0.22% O_2/day (due to permeation through the plastic layer and structural damage).

Fig. 8a shows the evolution of O_2 and CO_2 for

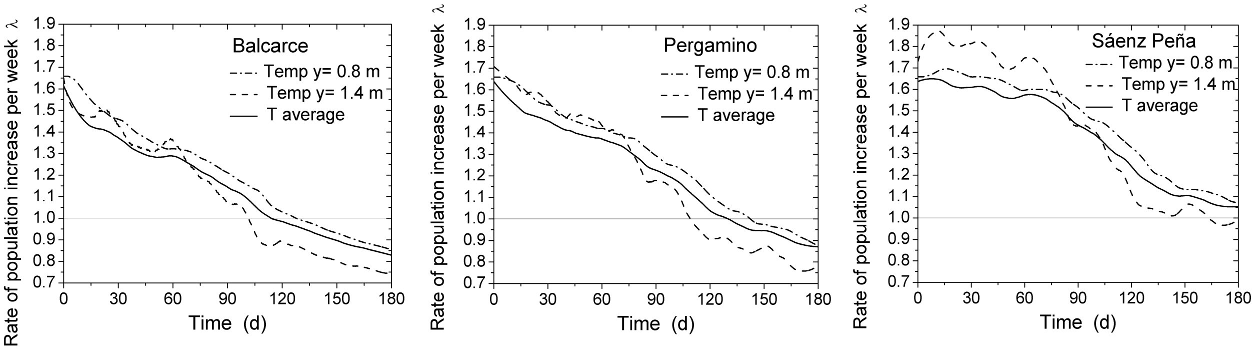

Fig. 6. Evolution of rate of population increase per week λ for *Sitophilus oryzae* at Balcarce, Pergamino and Sáenz Peña. Bagging conditions: wheat at 25ºC, 12% w.b.

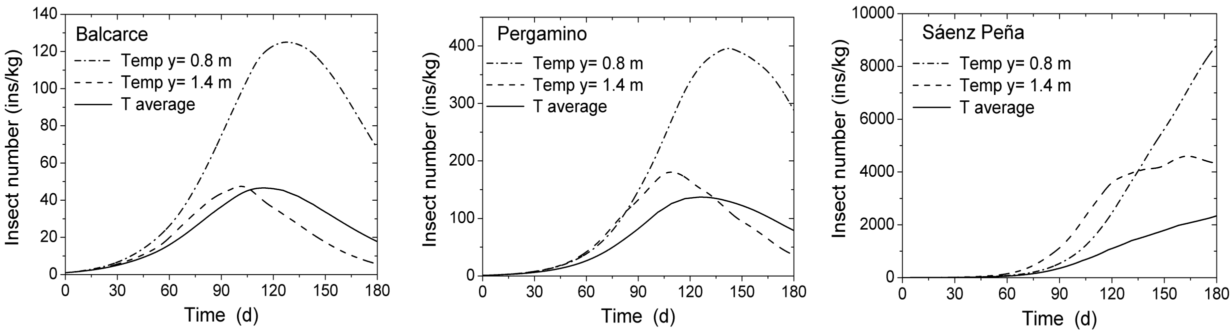

Fig. 7. Evolution of insect population for *Sitophilus oryzae* at Balcarce, Pergamino and Sáenz Peña. Bagging conditions: wheat at 25ºC, 12% w.b.

0.1 insect/kg. For comparison gas change in the silo bag without insects or structural damage (only the permeation through the plastic layer) are also plotted. This case (silo bag without insects or structural damage) will be named as "reference case" in the figures. It can be observed that with 0.1 insect/kg initial infestation, low O_2 level hostile to insect development were not achieved, as it remained above 10% V/V. Rate of population increase per week λ was driven by the temperature decrease (Fig. 8b) which produced a small decrease of the insect population by the end of storage (Fig. 8c).

Fig. 9a shows the evolution O_2 and CO_2 for 1 insect/kg. A fluctuating behaviour of gas concentration

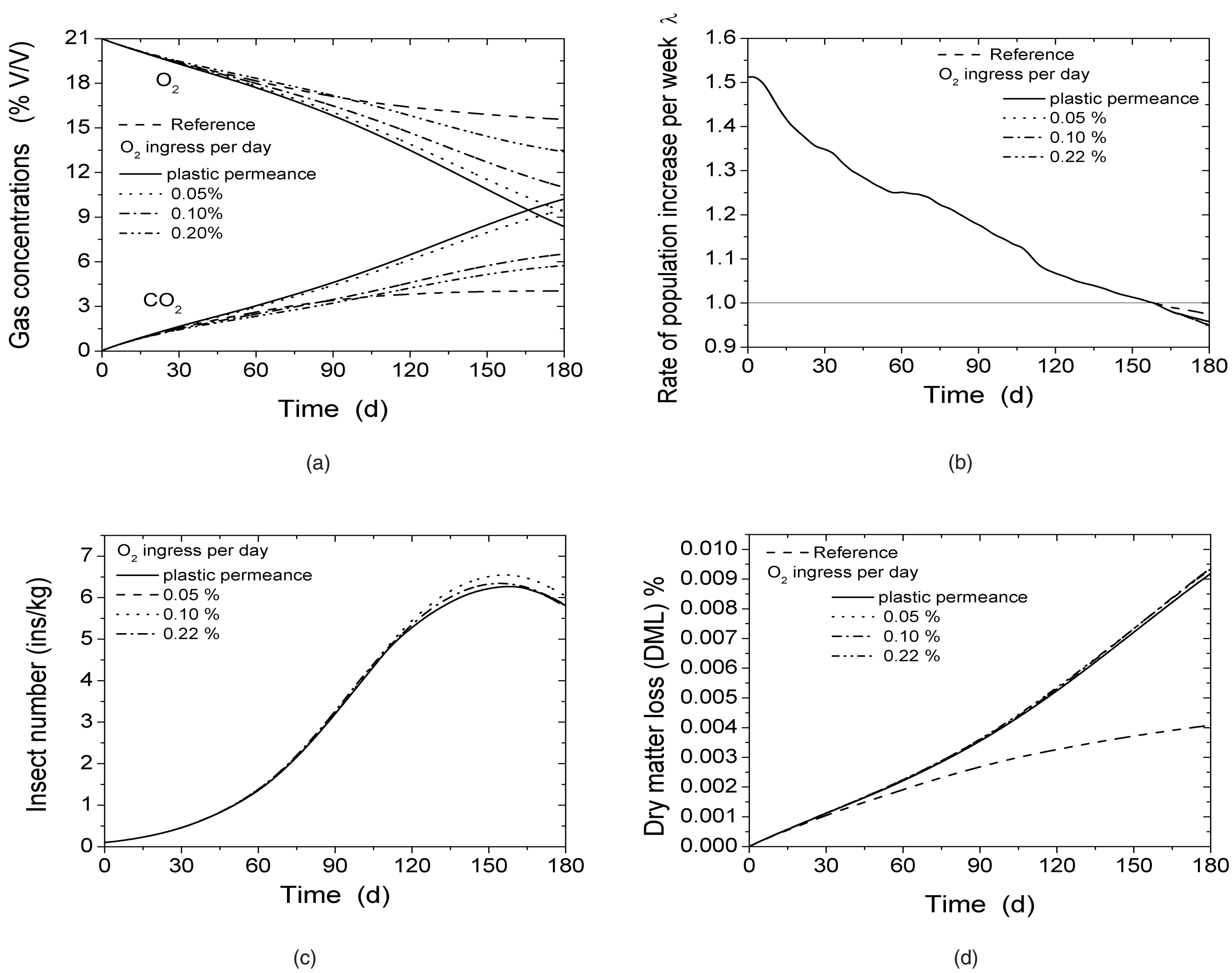

Fig. 8. Evolution O_2 and CO_2 (*a*), rate of population increase per week (*b*), insect population (*c*) and DML (*d*) initial infestation of 0.1 insect/kg

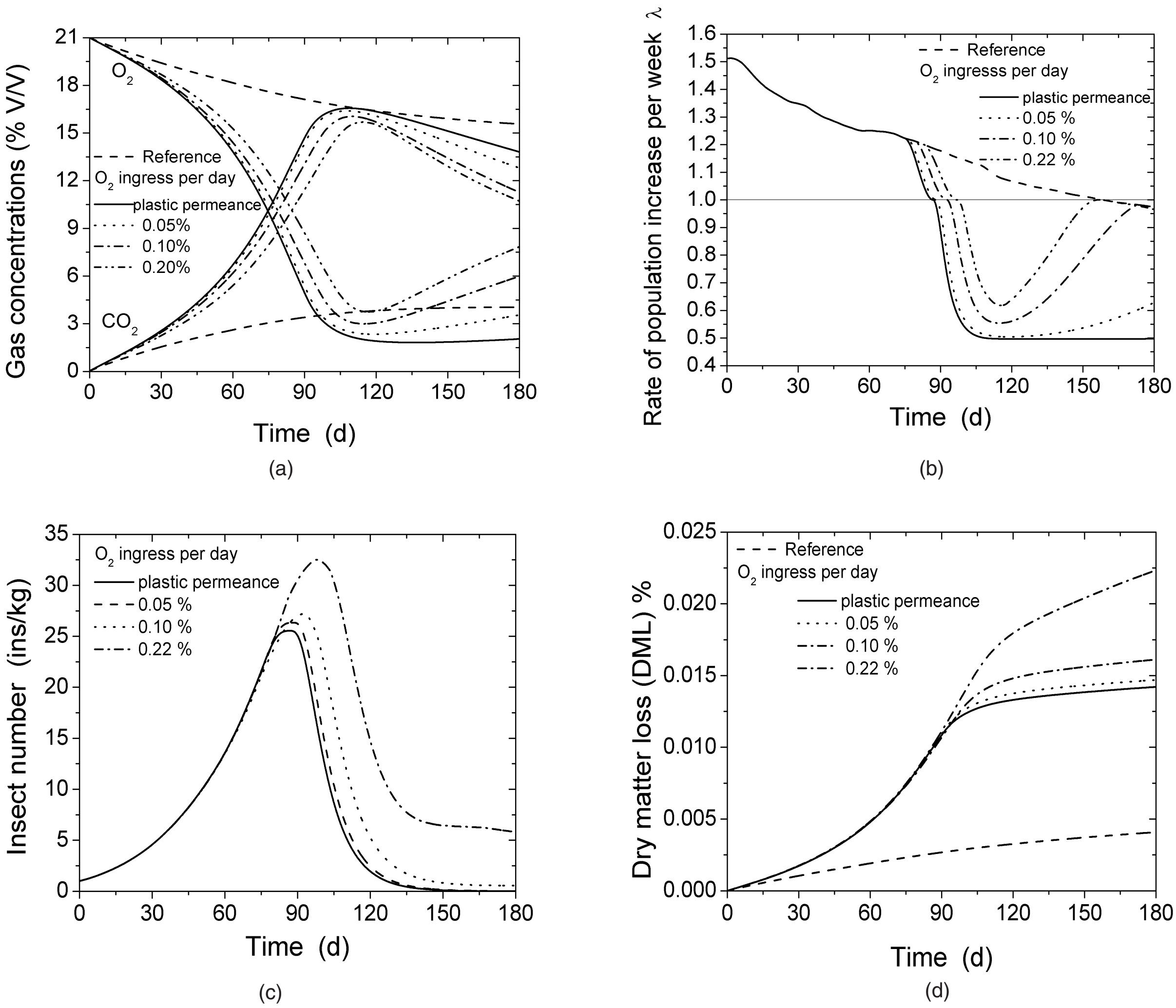

Fig. 9. Evolution O_2 and CO_2 (*a*), rate of population increase per week (*b*), insect population (*c*) and DML (*d*) initial infestation of 1 insect/kg

is obtained as O_2 ingress rate increases. For a silo bag without structural damage and 0.05% per day, O_2 concentration ranged from 2 to 5% V/V and insect density decreased to 0.001 insect/kg as shown in Fig. 9c while for 0.10% and 0.22% O_2 ingress per day, decreased to 0.5 insect/kg and 6 insects/kg respectively. Rate of population increase per week λ is shown in Fig. 9b. During the first month of storage, λ decayed driven by temperature and when O_2 fell below 10% V/V, according to the proposed correction factor. For higher O_2 ingress or longer storage time, an oscillatory behaviour in O_2 concentration would be observed, similar to the one shown in Fig. 3a.

Predicted DML for all the storage conditions (Fig. 8, Fig. 9d) did not exceed limits to reduce the grain commercial quality of 0.1% DML proposed by White et al. (1982). For 0.1 insect/kg initial infestation, DML at the end of storage doubled the value obtained for the reference case, and would continuously increase if insect development was not limited. For 1 insect/kg initial infestation, DML was three times higher than the reference case value. For O_2 ingress below 0.10% per day, DML tended to stabilized while continuously increased for 0.22% per day.

CONCLUSION

Population growth rates for *Rhyzopertha dominica* and *Sitophilus oryzae* were predicted as function of the grain temperature and intergranular relative humidity during storage from summer to winter of dry wheat for productive areas with sub-tropical, intermediate and moderate weather conditions. Results showed that the feasibility of insect control by the effect of temperature was rather weak for the Central and Southern regions of Argentina, while the rate of population increase per week remained above the unit for the sub-tropical region.

Evolution of gas concentration was predicted in an infested silo bag under moderate climate. For 0.1 insect/kg initial insect infestation, an interstitial atmosphere unfavourable for insect development was not achieved. For 1 insect/kg, O_2 concentration ranged from 2 to 5% V/V, arresting insect development if O_2 ingress per day remained below 0.05% per day.

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APPENDIX A

Navarro et al. (1994) predicted the change in O_2 concentration and dry matter loss (DML) in volume structure of 10 m^3 filed with corn (*Zea mays* L.) at 30°C. Initial infestation level was set 2, 4 and 8 insects/kg and O_2 ingress rate to 0.24%, 0.12% and 0.05%. Details on intrinsic rate of insect increase or how gas composition affected population dynamics, were not provided by the author. As temperature did not vary, the rate of population increase per week was assumed constant when O_2 level was above 10% V/V. Three variation of λ with O_2 were considered as illustrated in Fig. A1. Figure A2 and Figure A3 show that the evolution of O_2 and DML obtained with λ as fuction of $g_1(O_2)$ were comparable to those of Navarro et al. (1994).

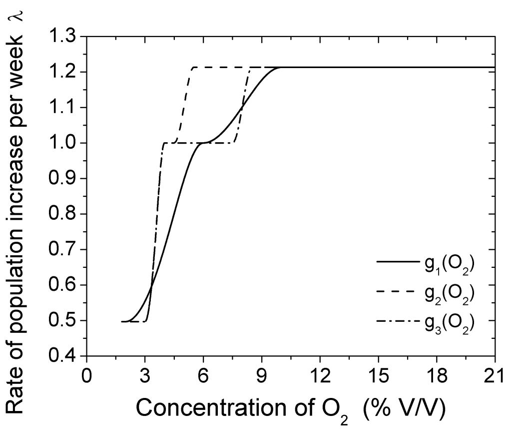

Fig. A1. Rate of population increase per week as function of O_2 concentration

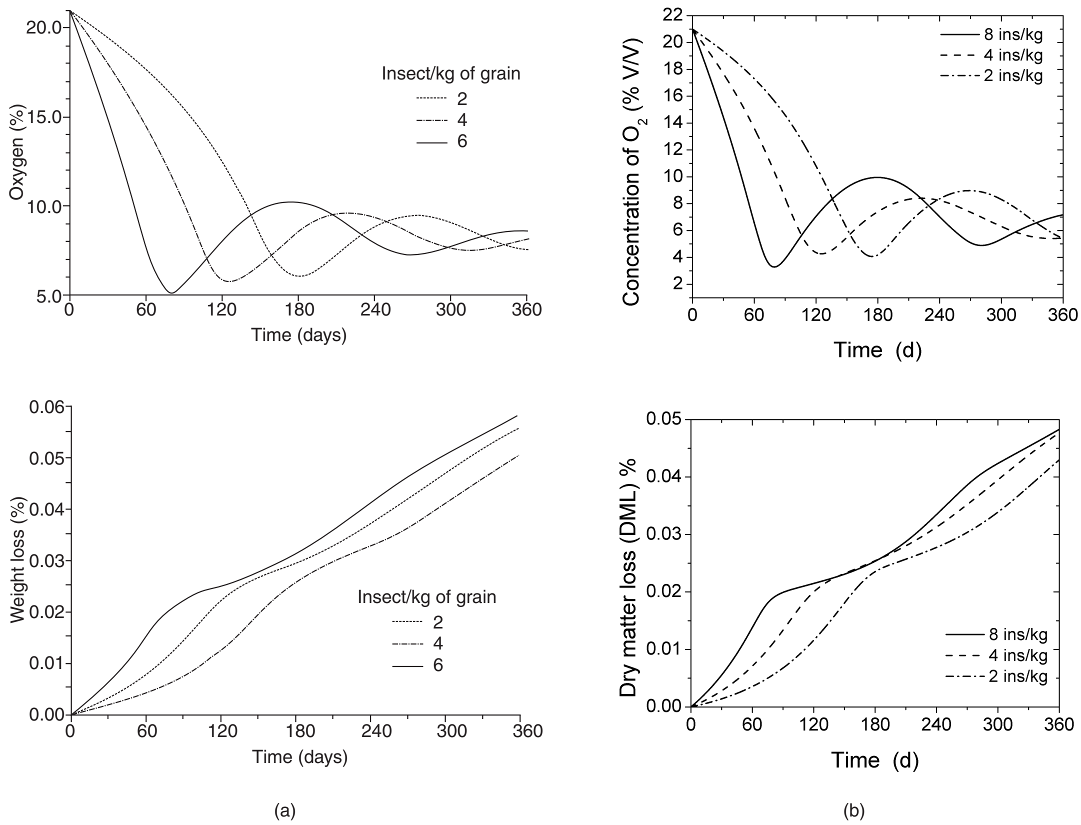

Fig. A2. O_2 concentration and dry matter loss (DML) estimated from a 10 m^3 of corn considering different levels of initial infestation, O_2 consumption of 157 µl/ins/d and a permeance of 0.24% O_2 per day through the plastic layer. (*a*) Navarro et al. (1994), (*b*) present work

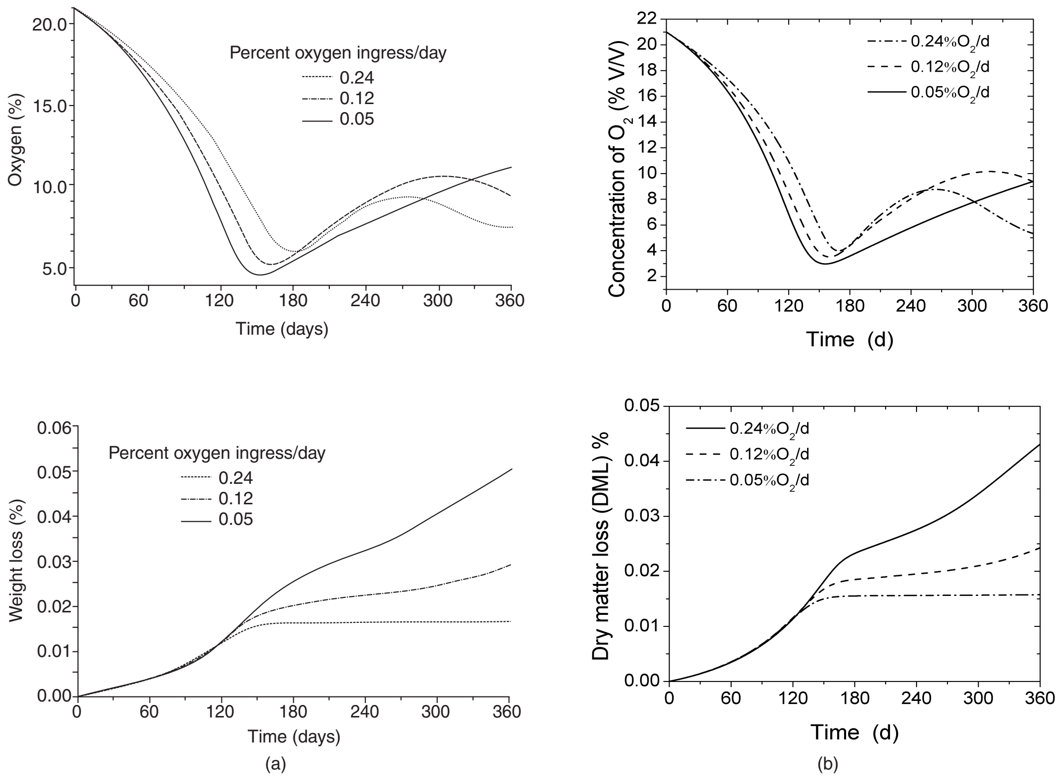

Fig. A3. O_2 concentration and dry matter loss (DML) estimated from a 10 m^3 of corn considering an initial infestation of 2 ins/kg, O_2 consumption of 157 µl/ins/d and different levels of permeance through the plastic layer. (*a*) Navarro et al. (1994), (*b*) present work