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Research Paper

Analysis of storage conditions of a wheat silo-bag for different weather conditions by computer simulation

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A validated mathematical model was used to analyse grain storage condition and determine the change in concentration of CO_2 in a silo-bag holding wheat from summer to winter for a typical productive region with sub-tropical (Saenz Peña, Chaco Province), intermediate (Pergamino, Buenos Aires Province) and temperate weather conditions (Balcarce, Buenos Aires Province) in Argentina. Initial moisture content of grain was set to 12, 14 and 16% w.b and bagging temperatures to 25 °C and 40 °C. For base conditions (12% w.b; 25 °C) CO_2 level increased to 4% V/V and O_2 decreased to 15.5% V/V in Balcarce while in Saenz Peña CO_2 level increased to 6% V/V and O_2 decreased to 13.9% V/V. For wet grain (16% w.b; 25 °C and 40 °C), O_2 depleted to less than 1% V/V at the three locations. The grain mean temperature in combination with the CO_2 and O_2 levels achieved in the silo-bags demonstrate that, for the climatic conditions of southern and central regions of Argentina, insect control is feasible in silo-bags. Mean dry matter loss for all the storage conditions was estimated and compared to the critical limit for safe storage of grain and seeds; it did not exceed limits that would reduce commercial quality, although seed could be affected when stored wet and during the summer.

1. Introduction

More than 40 million tonnes of grain (more than 40% of the total production of the country) were stored in hermetic systems (silo-bags) in the last harvest season in Argentina. Due to the successful experience of this technology during the last 15 years in Argentina, the silo-bag system is now being adopted in more than 40 countries worldwide, from countries with tropical weather (e.g. Sudan) to countries with cold weather (e.g. Russia).

This technique, originally used for grain silage, consists of storing dry grain in hermetically sealed plastic bags. The respiration process of the biological agents in the grain ecosystem (grain, insects, mites and microorganisms) consumes oxygen (O_2) and generates carbon dioxide (CO_2). Under adequate hermetic storage conditions, the resulting gas

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Notation

c_b specific heat capacity of grain bulk, $J\ kg^{-1}\ K^{-1}$
CO_2 CO_2 concentration, % V/V
D_w effective diffusivity of water vapour in intergranular air, s, $D_w = D_v\varepsilon/R_V\tau T$
D^*_i gas effective diffusivity through intergranular air, $m\ s^{-1}$, $i = CO_2, O_2$
D_{soil} soil thermal diffusivity, $m^2\ s^{-1}$
d_m local rate of dry matter consumed by aerobic respiration, mg [dry matter] kg^{-1} [dry matter] in 24 h
DML cumulative local dry matter loss at time t, mg [dry matter] kg^{-1} [dry matter]
$\overline{DML}$ cumulative mean dry matter loss at time t, mg [dry matter] kg^{-1} [dry matter]
D_v water vapour diffusivity in air, $m^2\ s^{-1}$
G incident solar radiation on the silo-bag surface, $W\ m^{-2}$
h_c convective heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
k_b thermal conductivity of grain bulk, $W\ m^{-1}\ K^{-1}$
L plastic layer thickness, m
L_g latent heat of vaporisation of moisture in the grain, $J\ kg^{-1}$, $L_g = RT^2(\partial \ln p_v/\partial T)_{W_g}$
M grain moisture content, % w.b
M_{CO2} molecular weight of carbon dioxide, 44 g mol^{-1}
n normal direction
O_2 O_2 concentration, % V/V
P_{atm} atmospheric pressure, 101,325 Pa
P_{CO2} equivalent permeability of CO_2 through plastic layer, $m^3\ m\ s^{-1}\ m^{-2}\ Pa^{-1}$
P_{O2} equivalent permeability of O_2 through plastic layer, $m^3\ m\ s^{-1}\ m^{-2}\ Pa^{-1}$
p_v partial pressure of water vapour, Pa
q_H heat released in respiration, 10.738 J mg^{-1} [CO_2]
q_w water vapour produced in respiration, 4.09 10^{-5} kg [H_2O] mg^{-1} [CO_2]
R gas constant, 8.314 J $mol^{-1}\ K^{-1}$
r_{CO2} rate of CO_2 production, $m^3\ s^{-1}\ kg^{-1}$ [dry matter]
r_{O2} rate of O_2 consumption, $m^3\ s^{-1}\ kg^{-1}$ [dry matter]
R_v water vapour gas constant, 461.52 J $kg^{-1}\ K^{-1}$
t time, s
T absolute temperature, K
T_c temperature, °C
T_i daily or annual soil temperature parameters, °C, i = 1, 2
$\overline{T}$ mean temperature, K
W_g grain moisture content, d.b
x, y Cartesian coordinates, m
Y_{CO2} rate of CO_2 production, mg [CO_2] kg^{-1} [dry matter] in 24 h

Greek symbols

β permeability quotient
ε porosity
Γ boundary domain
ω change in the partial pressure due to change in the temperature at constant moisture content, Pa K^{-1}, $\omega = \partial p_v(W_g, T_c)/\partial T|_{W_g}$
η change in the partial pressure due to change in the moisture content at constant temperature, Pa, $\eta = \partial p_v(W_g, T_c)/\partial W_g|_T$
Ω domain
α silo-bag surface absorptivity
φ daily or annual phase angle
σ Stefan–Boltzmann's constant, 5.6697 $10^{-8}\ W\ m^{-2}\ K^{-4}$
τ tortuosity factor
ξ emissivity
ψ daily or annual angular frequency, s^{-1}
ρ_{bs} dry bulk density, kg [dry matter] m^{-3}
θ storage time, days

Subscripts

amb ambient
sky sky
soil soil

concentrations promote a suitable environment for grain conservation.

Gas concentration depends on the balance between respiration of the ecosystem, the entrance of external O_2 into the system, and the loss of CO_2 to the ambient air. The transfer of gases depends on the gas partial pressure differential and the effective permeability of the plastic cover (openings and natural permeability of the plastic layer to gases). Grain type and condition, moisture content (MC), temperature, storage time and O_2 and CO_2 concentrations affect the biotic respiration rate.

The potential use of hermetic storage was discussed by Navarro, Donahaye, and Fishman (1994) who also conducted extensive research related to hermetic storage of wheat, corn and paddy in tropical climates (Donahaye et al., 2001; Donahaye, Navarro, Ziv, Blauschild, & Weerasinghe, 1991; Navarro, Caliboso, Sabio, & Donahaye, 1997; Navarro, Donahaye, Caliboso, & Sabio, 1996, 1998; Navarro, Donahaye, Ferizli, Rindner & Azrieli, 1998).

Silo-bags were locally adapted to store dry grain in Argentina more than 15 years ago. Since then, the National Institute of Agricultural Technologies of Argentina (INTA) has conducted sustained experimental research at the Experimental Stations (EEA) in Balcarce and Manfredi, addressing different aspects of hermetic storage in silo-bags. A set of field tests was carried out to analyse the effect of grain MC and storage time on the quality of wheat, corn, sunflower and soybean (Rodríguez, Bartosik, Malinarich, Exilart, & Nolasco, 2001, 2004; Rodríguez, Bartosik, Malinarich, & Maier, 2002) and barley (Bartosik, Ochandio, Cardoso, & de la Torre, 2012; Ochandio et al., 2010; Ochandio, Rodríguez, Rada, Cardoso, & Bartosik, 2009) stored in plastic bags. Santa Juliana and Casini (2009) studied the evolution of carbon dioxide and oxygen concentration in maize (*Zea mays* L.) grains stored in plastic bags while Cardoso, Bartosik, and Milanesio (2009), the change in phosphine concentration during fumigation of silo-bags. Cardoso, Bartosik, Campabadal, and de La Torre (2012) applied a pressure decay test to determine the initial air-tightness level of silo-bags and the change after four months of storage in the field. Recently Bartosik (2012) presented a summary of the investigations carried out so far in Argentina.

Furthermore, there has been research related to silo-bag storage in other countries. Darby and Caddick (2007) published an exhaustive analysis and field evaluation of silo-bag technology under typical Australian conditions. Bispo Dos Santos, Rodrigues de Brito, Martins, and Faroni (2008) analysed dry matter loss (DML) of maize grains stored hermetically. Ridley, Burrill, Cook, and Daglish (2011) investigated the potential of fumigation with phosphine to disinfest grain stored in silo bags. Idler, Wagne, Weber, and Hoffmann (2012) analysed the effect of short-term storage on quality of wheat stored in large polyethylene bags in comparison to conventional bulk storage.

At laboratory scale, Weinberg et al. (2008) studied the effect of moisture level on high moisture maize (*Zea mays* L.) under hermetic storage conditions while Ochandio, Bartosik, Yommi, and Cardoso (2012) analysed the evolution of carbon dioxide concentration in hermetic storage of soybean (*Glycine max*) in small glass jars.

A novel technology for monitoring grain storability in silo-bags based on CO_2 detection has been implemented by INTA in Argentina (Bartosik, Cardoso, & Rodríguez, 2008; Cardoso, Bartosik, Rodríguez, & Ochandio, 2008). The procedure consists of comparing the measured CO_2 concentration at some locations in the silo-bag (local concentration value) with a reference value which represents adequate storage conditions. It was observed that this reference value can change according to the season and climatic condition of a particular agricultural area (ambient temperature affects biotic respiration rate), thus, CO_2 reference values should be developed for each region. However, setting experimental field tests to cover the wide range of possible storage conditions is time consuming and costly, so a validated mathematical model is a powerful alternative to perform this kind of analysis.

Numerous numerical models have been developed for conventional storage systems and applied to analyse the storage of different grains, such as wheat (Jia, Sun, & Cao, 2000a, 2000b; Jiang, Jayas, White, & Alagusundaram, 2005; Khankari, Morey, & Patankar, 1994; Khankari, Patanakar, & Morey, 1995a, 1995b; Singh, Leonardi, & Thorpe, 1993); sorghum (Carrera-Rodríguez et al., 2011; Jiménez-Islas, Navarrete Bolaños, & Betello Alvarez, 2004); rice (Iguaz, Arroqui, Esnoz, & Vírseda, 2004a, 2004b) and corn (Andrade, Couto, Queiroz, & Faroni, 2002; Montross, Maier, & Haghighi, 2002a, 2002b) among others.

Regarding mathematical modelling, few references have been found in the international literature related to silo-bags. By numerical simulation, Bispo Dos Santos, Martins, and Faroni (2007) studied oxygen infiltration due to surface damage in a silo-bag holding wet maize and Lobo Paes, Martins, and Faroni (2007) analysed the possibility of accelerating anaerobiosis by use of oxygen depletion devices.

Bearing in mind the economic importance that grain production has for Argentina and the advantages of having a simulation tool for the analysis of hermetic storage, a comprehensive mathematical model for grain storage in silo-bags was developed based on the work of Thorpe (2002). For this purpose, first a heat and mass transfer model was developed to predict the evolution of temperature and MC distribution of grain stored in a silo-bag due to seasonal variation of climatic conditions, taking into account the heat and water vapour produced as a function of carbon dioxide released during respiration. Hermetic conditions to gas transfer were assumed for the silo-bag and the changes in the CO_2 concentration were estimated from the time integration of the rate production of CO_2 released. This model was validated by comparison of predicted and measured temperature, grain MC and mean O_2 and CO_2 concentrations (Gastón, Abalone, Bartosik, & Rodríguez, 2009). The standard errors of temperature in the model validation were 1.94 °C at the bottom, 1.35 °C in the middle and 1.20 °C at the toplayer of the bag. Since the MC measurements were few compared to temperature measurements, the global model validation was based mainly on temperature data as the heat transfer model is strongly coupled to the mass transfer model by source terms and moisture-dependent thermal properties.

New experimental data for gas composition in about 50 bags tested at grain elevators and farms in the South East of Buenos Aires province Bartosik, Cardoso et al. (2008) showed that it was necessary to improve gas concentration predictions. Therefore, to calculate the change in the mean O_2 and CO_2 concentrations, mass balances taking into account simultaneous O_2 consumption, CO_2 generation, and permeability of the plastic bag to gas transfer where coupled to energy and grain MC balances previously developed. Based on the experimental evidence that no gas stratification was detected in the silo-bag, the model assumed a uniform gas distribution resulting in lumped CO_2 and O_2 balance equations. The rates of CO_2/O_2 production/consumption were evaluated at the mean temperature and MC of the grain. The mean temperature changes according to seasonal variation of weather conditions while the mean MC remains constant as the silo-bag was considered impermeable to water vapour.

Validation of the improved model (Model 1) was carried out by comparison of predicted mean O_2 and CO_2 concentrations with the new experimental data (Abalone, Gastón, Bartosik, Cardoso, & Rodríguez, 2011a). The general trends of measured gas concentrations were comparable with the simulated ones. In the dry MC range (12–13.5% w.b) standard error (SE) for CO_2 was 1.2% V/V while in the wet range of (14–15% w.b) increased to 2.7% V/V. For O_2, SE was 2.5% V/V for dry and 1.9% V/V for wet MC range, respectively.

Sensitivity of Model 1 to silo-bag permeability and respiration rate was investigated as well as the effect of grain storage conditions on gas concentration in a wheat silo-bag (Abalone, Gastón, Bartosik, Cardoso, & Rodríguez, 2011b). Results showed that gas concentration was more sensitive to changes in respiration rate than to permeability of the plastic film. Considerable changes occur in gas concentration in a damaged silo-bag. The definition of an effective permeability to account for gas transfer through holes and plastic film allowed the examination of the effect of different hole configurations (number and size of perforations) on the gas concentration.

To address the mass transport processes inside the silo-bag, diffusion of gases was subsequently incorporated into the CO_2 and O_2 balances in order to predict temperature and grain MC as well as gas distribution and concentration gradients in the silo-bag with a new set of equations (Model 2). The mean gas concentrations predicted with Model 1 and Model 2 were compared for a range of initial conditions (20–40 °C, 12–16% w.b). Comparisons for the worst bagging conditions showed that for dry and hot wheat (40 °C, 12% w.b), differences were negligible while for wet wheat (40 °C, 16% w.b) the difference was less than 1% V/V (Abalone & Gastón, 2011; Arias Barreto, Abalone, & Gastón, 2011). The validation of Model 2 using the same data as before resulted in an SE of the same order of magnitude as the SE of Model 1.

Though averaging local temperature and moisture gradients has a small effect on the prediction of mean gas concentration, the inclusion of diffusion gas transport in Model 2 was important for the analysis of local effects in the silo-bag that cannot be addressed with Model 1, for example when a non-uniform initial MC distribution is considered, as discussed in Abalone & Gastón, 2011 and Arias Barreto et al. (2011).

Owing to the high ratio of transfer area/grain volume of the silo-bag, temperature monitoring is not a reliable method to detect biological activity (Gastón et al., 2009), and storability conditions of grains in silo-bags are better addressed through CO_2 detection (Bartosik, Cardoso et al., 2008; Cardoso et al., 2008; Ileleji, Maier, Blat, & Woloshuk, 2006). Abalone et al. (2011b) showed by numerical simulation that the reference levels of CO_2 indicating adequate storage conditions were strongly dependent on initial MC and bagging grain temperature, a variable which in turn will change according to the weather conditions of the particular agricultural area during storage.

In the present work, Model 2 was used to analyse the storage conditions of a silo-bag holding wheat in three production regions of Argentina, one in the North (Saenz Peña, Chaco Province (26.87°S, 60.45°W)) with sub-tropical weather conditions, one in the Centre (Pergamino, Buenos Aires Province, (33.93°S, 60.55°W)) with intermediate weather conditions and the other one in the South (Balcarce, Buenos Aires Province (37.75°S, 58.30°W)) with temperate weather conditions. The grain temperature, MC and DML, as well as O_2 and CO_2 concentrations were simulated during six months, from summer to winter. The effect of initial MC and bagging temperatures was investigated. Reference mean O_2 and CO_2 concentrations that correspond to the three locations and mean DML for all the storage conditions were estimated and compared to the critical limit for safe storage of seeds.

2. Materials and method

2.1. Silo-bags

Silo-bags are 60 m long, 2.70 m diameter and 230–250 microns thick. Approximately 200 tonnes of grains (wheat, corn or soybean) can be held in the bag and usually farmers store their production for six to eight months. The bags are made of a three-layer plastic, black on the inner side and white on the outer side with UV stabilisers. The plastic layers are a mixture of high density (HDPE) and low density polyethylene (LDPE).

2.2. Mathematical modelling

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 is derived:

$$c_b\rho_{bs}\frac{\partial T}{\partial t}=\left[\frac{\partial}{\partial x}\left[k_b\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[k_b\frac{\partial T}{\partial y}\right]\right]+\rho_{bs}L_g\frac{\partial W_g}{\partial t}+\rho_{bs}q_H Y_{CO2}\ \text{in}\ \Omega_1 \quad (1)$$

$$\rho_{bs}\frac{\partial W_g}{\partial t}=\frac{\partial}{\partial x}\left[D_w\left(\eta\frac{\partial W_g}{\partial x}+\omega\frac{\partial T}{\partial x}\right)\right]+\frac{\partial}{\partial y}\left[D_w\left(\eta\frac{\partial W_g}{\partial y}+\omega\frac{\partial T}{\partial y}\right)\right]+\rho_{bs}q_w Y_{CO2}\ \text{in}\ \Omega_1 \quad (2)$$

$$\varepsilon\frac{\partial CO_2}{\partial t}=\frac{\partial}{\partial x}\left[D^*_{CO2}\left(\frac{\partial CO_2}{\partial x}\right)\right]+\frac{\partial}{\partial y}\left[D^*_{CO2}\left(\frac{\partial CO_2}{\partial y}\right)\right]+\rho_{bs}r_{CO2}\ \text{in}\ \Omega_1 \quad (3)$$

$$\varepsilon\frac{\partial O_2}{\partial t}=\frac{\partial}{\partial x}\left[D^*_{O2}\left(\frac{\partial O_2}{\partial x}\right)\right]+\frac{\partial}{\partial y}\left[D^*_{O2}\left(\frac{\partial O_2}{\partial y}\right)\right]+\rho_{bs}r_{O2}\ \text{in}\ \Omega_1 \quad (4)$$

where T in K is temperature, W_g is grain MC (d.b), O_2 and CO_2 (% V/V) are oxygen and carbon dioxide concentrations, ε porosity, ρ_{bs} in kg m^{-3} is dry bulk density, c_b in J kg^{-1} K^{-1} is bulk specific heat, k_b in W m^{-1} K^{-1} is bulk thermal conductivity, D_w is an effective diffusivity parameter for water vapour, L_g in J kg^{-1} is the latent heat of vaporisation of moisture in the grain, η in Pa is the change in the partial pressure due to change in the MC at constant temperature, ω in Pa K^{-1} is the change in the partial pressure due to change in the temperature at constant MC, D^*_i in m^2 s^{-1} (with i = CO_2 or O_2) is the effective diffusivity through the intergranular air of carbon dioxide and oxygen calculated according to Geankoplis (1998) and Thorpe (1981).

In Eqs. (1)–(4), the last term represents heat, water vapour and carbon dioxide released and oxygen consumed, respectively, owing to respiration of the grain ecosystem. Respiration is modelled by the complete combustion of a typical carbohydrate. Y_{CO2} is the rate of CO_2 production, in mg [CO_2] kg^{-1} [dry matter] s^{-1}, q_H is 10.738 J mg^{-1} [CO_2], q_w is 4.09 10^{-5} kg [H_2O] mg^{-1} [CO_2]. The rate of CO_2 production r_{CO2} in m^3 s^{-1} kg^{-1} [dry matter] is given by:

$$r_{CO2}=\frac{Y_{CO2}}{1000M_{CO2}}\frac{RT}{P_{at}}\ ;\ r_{O2}=r_{CO2} \quad (5)$$

Boundary conditions associated with Eqs. (1)–(4) are given by:

$$-k_b\frac{\partial T}{\partial n}=h_c(T-T_{amb})-\alpha G+\xi\sigma\left(T^4-T^4_{sky}\right)\ \text{on}\ \Gamma_1 \quad (6)$$

$$\sigma T^4_{sky}=\xi_{sky}\sigma T^4_{amb} \quad (7)$$

$$T=T_{soil}(y,t)=T_1(y)+T_2\exp\left(-y\sqrt{\frac{2\Psi}{D_{soil}}}\right)\left[\cos\left(\Psi t-y\sqrt{\frac{2\Psi}{D_{soil}}}-\phi\right)\right]\ \text{on}\ \Gamma_3 \quad (8)$$

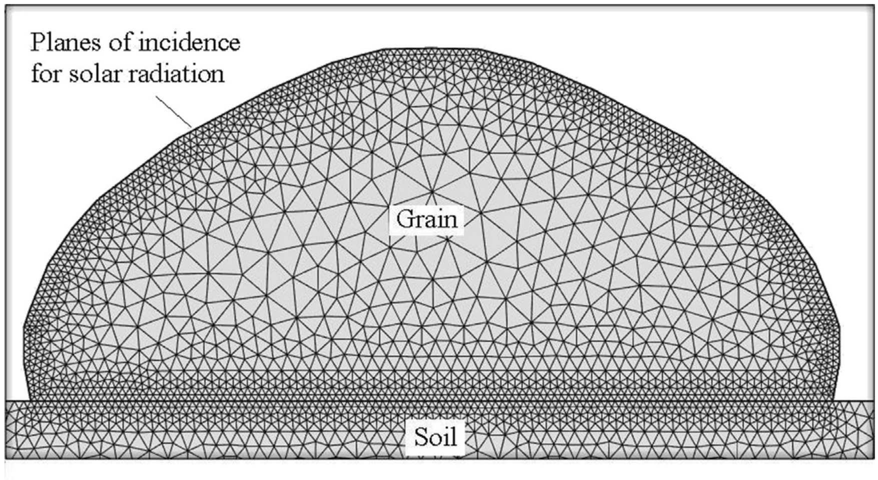

Fig. 1 – Cross section of the silo-bag and discretization domain.

$$\frac{\partial p_v}{\partial n} = 0 \Rightarrow \eta D_w \frac{\partial W_g}{\partial n} = -\omega D_w \frac{\partial T}{\partial n} \text{ on } \Gamma_1 + \Gamma_2 \tag{9}$$

$$-D^*_{CO2}\frac{\partial CO_2}{\partial n} = \frac{P_{CO2}P_{atm}}{L}(CO_2 - CO_{2out}) \text{ on } \Gamma_1 \tag{10}$$

$$-D^*_{O2}\frac{\partial O_2}{\partial n} = \frac{P_{O2}P_{atm}}{L}(O_2 - O_{2out}) \text{ on } \Gamma_1 \tag{11}$$

Boundary conditions considered solar radiation and convection to the surroundings (Eq. (6)) as well as the interaction between the soil and the bottom layer of the silo-bag (Eq. (8)). It was assumed that the silo-bag was impermeable to moisture transfer (Eq. (9)). Gas transfer through the plastic layer was modelled by defining an equivalent permeability of the plastic to O_2 and CO_2 (Eq. (10) and Eq. (11)).

According to the stoichiometric respiration equation (complete combustion of a typical carbohydrate), the rate of dry matter consumed by aerobic respiration d_m in mg [dry matter] kg^{-1} [dry matter] in 24 h is computed by:

$$d_m(x, y, t) = \frac{180 \text{ g}}{264 \text{ g}} Y_{CO2}(x, y, t) \tag{12}$$

The cumulative local dry matter loss (DML) in mg [dry matter] kg^{-1} [dry matter] at time t was calculated by integration over time:

$$DML(x, y, t) = \int_0^t d_m(x, y, t')dt' \tag{13}$$

while mean values of cumulative dry matter loss and temperature are calculated as follows:

$$\overline{DML}(t) = \frac{1}{\Omega}\int_\Omega DML(x, y, t)\ d\Omega \tag{14}$$

$$\overline{T}(t) = \frac{1}{\Omega}\int_\Omega T(x, y, t)\ d\Omega \tag{15}$$

2.3. *Input model parameters*

Dependence of the rate of CO_2 production Y_{CO2} for wheat was evaluated by use of the correlation developed by White, Sinha, and Muir (1982):

$$\log Y_{CO2} = -4.054 + 0.0406T_c - 0.0165\theta + 0.0001\theta^2 + 0.2389M \tag{16}$$

where Y_{CO2} is in mg kg^{-1} of dry matter in 24 h, θ is the storage time in days, T_c is grain temperature in °C and M is moisture content in % w.b.

It is important to remark that in Argentina, as in most grain-producing countries, the stored product pests are seldom present in the field, so the possibility of bagging infested wheat is rather low. In addition to that, the typical bagging operation is very simple (combine to grain cart to bagging machine) in comparison with sending the grain to an elevator, where a larger number of steps are involved until the grain is stored in a bin, resulting in a higher risk of insect infestation. Another key point is that the silo-bags are not reusable, so every time the grain is bagged, the bag is new and hence free of insects. Also, 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. As a result, there have been few reports of silo-bags infested with insects. Massigoge, Cardoso, Bartosik, Rodríguez, and Ochandio (2010) reported that in a study where 56 barley silo-bags were monitored during 6 months (from harvest in early summer until winter), insects were detected in only 6 silo-bags. It was also noticed that insects were observed only during the warm season of storage (summer). As the storage season progresses into the fall and winter, the temperature of the grain inside the silo-bag follows the average ambient temperature and drops to 8–15 °C (Bartosik, Rodriguez et al., 2008; Gastón et al., 2009), below the limit for insect activity (13–17 °C) (Banks & Fields, 1995; Field & Muir, 1996). This implies that, for the region in which the study was carried out, there is a low probability that infested grain would come from the field at the time of being bagged, and that, if that did occur, the insects

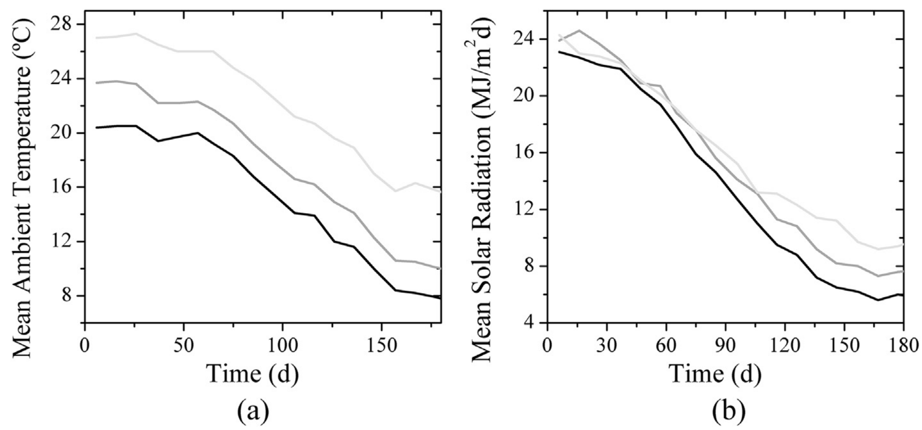

Fig. 2 – Comparison of a) mean ambient temperature and b) solar radiation of agricultural areas; —, Balcarce; —, Pergamino; —, Saenz Peña.

would not develop significantly during storage in the silo-bag due to the low temperature during the cold season. Based on the considerations listed above, no contribution of insect respiration to CO_2 production was included in this study.

Sorption equilibrium was modelled by the Modified Henderson equation (Brooker, Bakker-Arkema, & Hall, 1992) and model parameters L_g, η, and ω derived accordingly.

The equivalent permeability of the silo-bag to O_2 and CO_2 was calculated by use of a resistance series model. Assuming that half of the plastic layer thickness was HDPE and the other LDPE polyethylene, estimated equivalent permeability to O_2 was 1.11 10^{-17} m^3 m s^{-1} m^{-2} Pa^{-1} and to CO_2 was 3.67 10^{-17} m^3 m s^{-1} m^{-2} Pa^{-1}, being the permeability quotient $\beta = P_{CO2}/P_{O2} \cong 3$.

A detailed description of the model has been presented in previous publications (Abalone et al., 2011a, b; Abalone, Gastón, Cassinera, & Lara, 2006; Gastón et al., 2009).

2.4. Numerical solution

The mathematical model was implemented using COMSOL Multiphysics 4.2a and solved numerically by the finite element method. Figure 1 shows the calculation domain, which represents a cross section of the silo-bag. A refined mesh was generated at the boundaries were the highest temperature and moisture gradients are expected to occur. Quadratic Lagrangian elements and a fourth order numerical quadrature were applied. UMFPACK solver was selected to solve the PDE system (unsymmetrical multifrontal method and direct sparse LU factorisation).

3. Results and discussion

3.1. Definition of initial bagging conditions and weather data for simulation

The model was applied to analyse the storage of wheat in a silo-bag from January to June (six months). Initial grain MC was set to 12, 14 and 16% w.b and initial bagging temperatures to 25 °C and 40 °C. Weather data corresponding to 1997–2004 years were considered for Balcarce (37.84°S; 58.26°W), to 2001–2006 years for Pergamino (33.85°S; 60.93°W), and to 1999–2006 years for Saenz Peña (26.78°S; 60.45°W).

Figure 2 compares annual mean temperature and mean solar radiation at the three locations. In summer, mean ambient temperature in Saenz Peña is about 3 °C higher than in Pergamino and 7 °C higher than in Balcarce, while in winter the temperature is about 6 °C and 8 °C higher, respectively. In summer, mean solar radiation is comparable in Saenz Peña and Pergamino and about 9% higher than in Balcarce. In autumn, irradiance in Saenz Peña is about 13% and 30% higher than in Pergamino and Balcarce, respectively.

Results for each bagging condition were averaged over the computed years for each location and a 90% confidence interval for temperature, CO_2 and O_2 and DML was constructed by applying a *t*-Student probability distribution.

3.2. Comparison CO_2 and O_2 concentration levels

Comparison of gas reference levels for the three agricultural areas is given in terms of the time-course of mean CO_2 and O_2 concentrations. Abalone and Gastón (2011) showed that concentration differences along a vertical line in the cross section of a silo-bag were of the order of 0.05% V/V and that concentration values at different locations in the bag were almost equal to the mean value (assuming uniform bagging conditions). This also means that gas sampling at one or two locations would be enough to obtain reliable information about the grain storability condition, at least in the cross section of the silo-bag. Besides, such small concentration differences between the top and bottom of the bag would hardly be detectable in large scale field tests, in accordance with Bartosik, Cardoso et al. (2008) and Cardoso et al. (2008) who reported that gas distribution in silo-bags in the field was almost uniform.

Figure 3 shows the mean gas concentration at the three locations for 25 °C initial bagging temperature. It can be appreciated that climatic conditions produce significant changes in reference levels after 180 days of storage, especially for 12% and 14% w.b. In Balcarce, CO_2 level increased to 4.03 ± 0.07% V/V and O_2 decreased to 15.5 ± 0.1% V/V for 12%

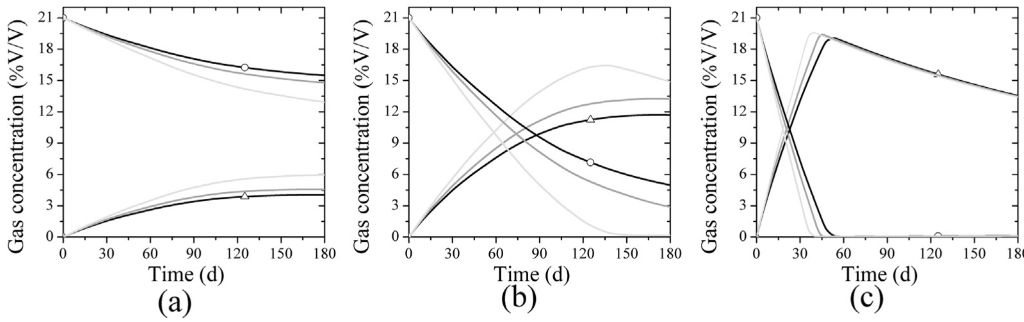

Fig. 3 – Concentration evolution of CO_2 (△) and O_2 (○) for a) 12% w.b; b) 14% w.b and c) 16% w.b; —, Balcarce; —, Pergamino; —, Saenz Peña. Initial bagging temperature: 25 °C.

w.b. An increment of 3 °C in ambient temperature shifts CO_2 and O_2 levels to 4.6 ± 0.1% V/V and 14.8 ± 0.1% V/V in Pergamino, and one of 8 °C to 6.0 ± 0.1% V/V and 13.9 ± 0.2% V/V in Saenz Peña. Differences in the concentration levels between summer (40 days) and winter (180 days) remained within 3% V/V points approximately at the three locations.

At 14% w.b mould activity becomes important, increasing CO_2 concentration to 11.7 ± 0.2% V/V and reducing O_2 concentration to 5.0 ± 0.3% V/V at Balcarce and to 13.2 ± 0.3% V/V and to 2.9 ± 0.4% V/V at Pergamino. Differences of up to 7% V/V points between summer (40 days) and winter (180 days) were found. At Saenz Peña, O_2 is almost consumed after 140 days and remained at zero thereafter because all the O_2 entering through the plastic cover is consumed by respiration. CO_2 reached 14.9 ± 0.1% V/V and then decayed as a result of the permeability of CO_2 through the plastic layer, which is about three times greater than that of O_2 ($\beta = 3$). For 16% w.b, O_2 depleted to less than 1% V/V within 40–50 days (Saenz Peña and Balcarce) and CO_2 increased as explained before.

Figure 4 shows results for 40 °C initial temperature. For 12% w.b, CO_2 increased 1.0–1.5% V/V with respect to 25 °C, while O_2 decreased by the same amount. For 14% w.b, O_2 depleted to less than 1% V/V after 90 days in Saenz Peña, 140 days in Pergamino and 180 days in Balcarce while at 16% w.b this condition was achieved in about 20 days at the three locations.

3.3. *Comparison of silo-bag temperature changes*

Numerical results presented in Gastón et al. (2009) revealed that temperature and moisture gradients were concentrated below the silo-bag surface within a layer of 0.10–0.20 m thick. This means that roughly 25% of the stored grain followed the hourly fluctuations of weather climatic conditions and in consequence would be exposed to greater quality losses and spoilage. Therefore, the change of temperature during the storage period at two locations in the silo-bag, close to the plastic surface ($y = 1.4$ m) and in the middle ($y = 0.8$ m), will be illustrated together with the mean temperature of the silo-bag. For a given initial bagging temperature, results for 12, 14 and 16% w.b were almost identical, thus only those corresponding to 16% w.b initial MC (worst storage condition) are shown in Fig. 5 for 25 °C and Fig. 6 for 40 °C. Below the surface, temperature oscillated with average amplitude of 5 °C in summer and 2.5 °C in winter. In Balcarce and Pergamino, the average temperature at the top started to decrease from the beginning for both initial temperatures, while in Saenz Peña, for the moderate initial bagging temperature (25 °C), warmer ambient conditions made the top temperature increased about 2.5 °C during the summer. Oscillations were completely attenuated in the middle of the bag ($y = 0.8$ m), and temperature continuously decreased even for moist grain (16% w.b) as a result of heat exchange with the surroundings.

Figure 7 compares the mean temperature of the silo-bags at the three locations for 16% w.b, 25 °C and 40 °C initial temperatures. These results demonstrate that for the Central and Southern regions of Argentina, insect activity would be limited for dry and moist grain because the mean temperature of grain decreases below 17 °C during autumn and winter preventing insect infestation. Moreover, even in summer conditions, grain at 14% w.b or higher, would limit insect activity as a result of low O_2 and high CO_2 concentration in the silo-bag, if the silo-bag maintains a high air tightness level. On

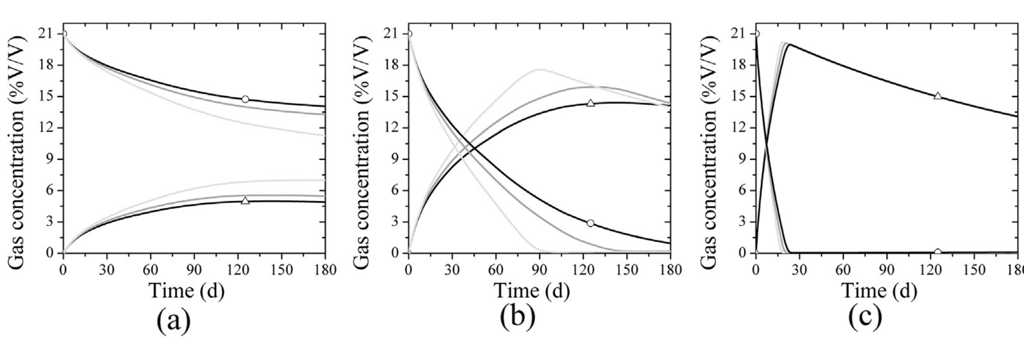

Fig. 4 – Concentration evolution of CO_2 (△) and O_2 (○) for a) 12% w.b; b) 14% w.b and c) 16% w.b; —, Balcarce; —, Pergamino; —, Saenz Peña. Initial bagging temperature: 40 °C.

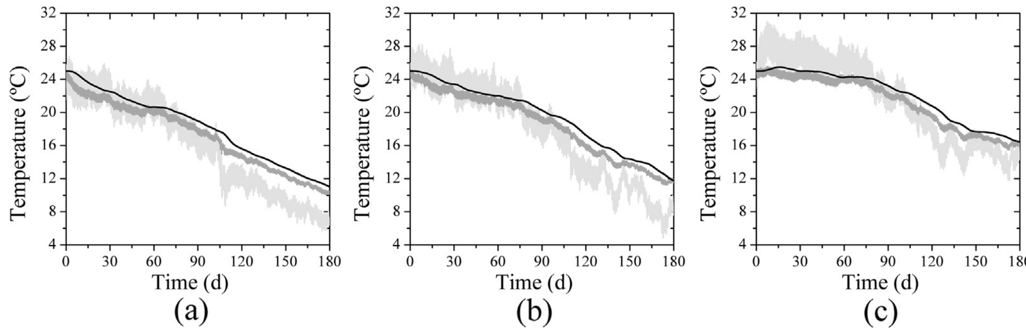

Fig. 5 – Grain temperature evolution at a) Balcarce, b) Pergamino and c) Saenz Peña. —, mean temperature; —, temperature at y = 0.8 m; —, temperature at y = 1.4 m. Bagging conditions: 16% w.b, 25 °C.

the contrary, when storing dry wheat (e.g. 12% w.b), insect infestation could develop during summer and early autumn (or during the entire year in regions with tropical weather) since neither temperature nor O_2 and CO_2 concentrations would be limiting. An additional advantage of the silo-bags with regard to insect infestation is that the silo-bags are not reusable, so every time the grain is bagged, the bag is new and hence, it is free of insects (there is no permanent infestation as can be possible in permanent storage structures), 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.

Moisture redistribution was also computed and occurred in the opposite direction to temperature gradients in the silo-bag. Therefore, moisture migrated mainly towards the surface and, to a lesser extent, to the bottom of the silo-bag as shown in previous work (Gastón, Abalone, Bartosik, & Rodríguez, 2008, 2009). On average, moisture accumulation at the top layer (y = 1.4 m) was at most 0.2% w.b at the three locations for 25 °C initial bagging temperature and 0.3% w.b points for 40 °C.

By use of the sorption isotherm, equilibrium relative humidity (ERH) was predicted. Safe storage condition (ERH < 70%) hold from summer to winter for 12% and 14% w.b initial MC. For 16% w.b, interstitial ERH was always higher than 70% during the warm season and during winter the ERH at the top layer (y = 1.4 m) decreased as grain cooled because of climatic conditions, but not enough to bring ERH to safe levels (Figs. 8 and 9). These results reveal the importance of maintaining gas tightness of the silo-bag, especially when storing wet grain. Though wet grain creates anaerobic conditions preventing microflora activity (Weinberg et al., 2008), any leakage would be favourable for supporting aerobic mould activity causing damage and reducing the safe storage time.

3.4. *Comparison of dry matter loss (DML)*

To estimate the effect of storage conditions on grain quality, DML was calculated. White et al. (1982) considered that a 0.1% DML is unacceptable for wheat, and if stored wheat is to be used as seed, the safe storage limit is 0.04% DML.

Figure 10 illustrates local DML (y = 1.4 m and 0.8 m) as well as mean DML for the wheat silo-bag at 16% w.b, 25 and 40 °C at the three locations. For the worst storage condition, wheat at 16% w.b and 40 °C, mean DML was on average (0.015 ± 0.004)% after nearly 20 days. Thereafter, DML increase would presumably be very small due to respiration inhibition, as O_2 level predicted by the model remained very low as shown in Fig. 4. The dashed lines in Fig. 10 would give an estimate of the amount of mean DML produced in a silo-bag that is not gas-tight so that oxygen is available unrestrictedly for respiration. In such a case, DML would exceed safe limits for wheat used for seed but not high enough to reduce grain's commercial quality. These results are in agreement with field data showing that when seeds are stored with low MC (ERH below 67%), no substantial reduction in the germination test was observed for wheat and soybean (Bartosik, Rodríguez, & Cardoso, 2008) and barley (Massigoge et al., 2010; Ochandio et al., 2009, 2010), even when the storage time was extended to the summer season.

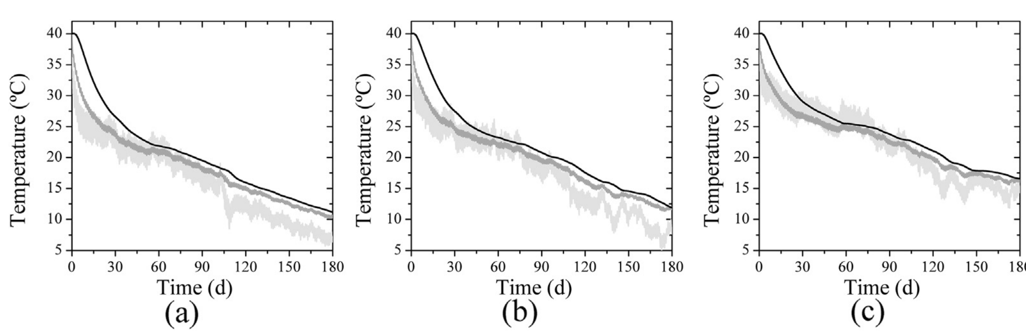

Fig. 6 – Grain temperature evolution at a) Balcarce, b) Pergamino and c) Saenz Peña. —, mean temperature; —, temperature at y = 0.8 m; —, temperature at y = 1.4 m. Bagging conditions: 16% w.b, 40 °C.

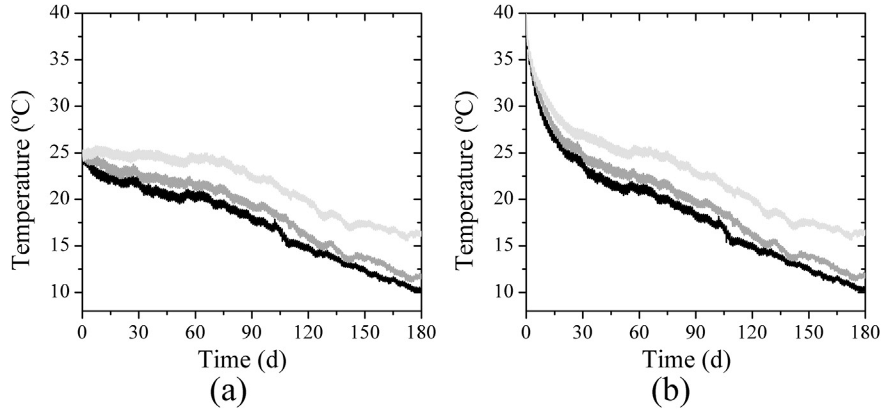

Fig. 7 – Comparison of grain mean temperature evolution at the three agricultural areas. Balcarce (—), Pergamino (—) and Saenz Peña (—). Bagging temperature: a) 25 °C; b) 40 °C. Bagging moisture content: 16% w.b.

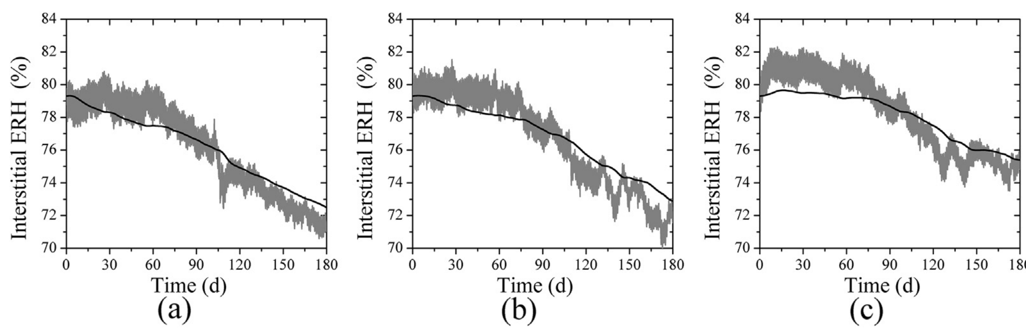

Fig. 8 – Equilibrium relative humidity (ERH) evolution at a) Balcarce, b) Pergamino and c) Saenz Peña. —, ERH at y = 0.8 m; —, ERH at y = 1.4 m. Bagging conditions: 16% w.b, 25 °C.

In addition, it can be observed that the location with higher DML depends on the initial bagging temperature. For 25 °C, DML at the top layer was higher than in the middle while at 40 °C the behaviour was reversed. As result of energy exchange with the surrounding, the average rate of respiration was higher at the top layer (y = 1.4 m) because the temperature (initially 25 °C) increased and remained above the temperature in the middle (0.8 m) during the warm season (first 80 days in Fig. 5). When wheat was bagged at 40 °C, the core of the silo-bag remained hotter than the surface layer which cooled down due to climatic conditions, thus inverting the respiration rate. Based on this observation, a gradient of seed quality could be developed in the silo-bag profile during storage, and thus the recommendation is to probe the entire profile of the bagged grain in order to obtain reliable information of the seed quality.

4. Conclusions

The effect of climatic conditions on the gas concentration in silo-bags holding wheat as well as grain storage condition was analysed by use of a validated mathematical model. Reference mean O_2 and CO_2 levels were predicted for a typical productive region with sub-tropical (Saenz Peña, Chaco Province), intermediate (Pergamino, Buenos Aires Province) and temperate weather conditions (Balcarce, Buenos Aires Province) of

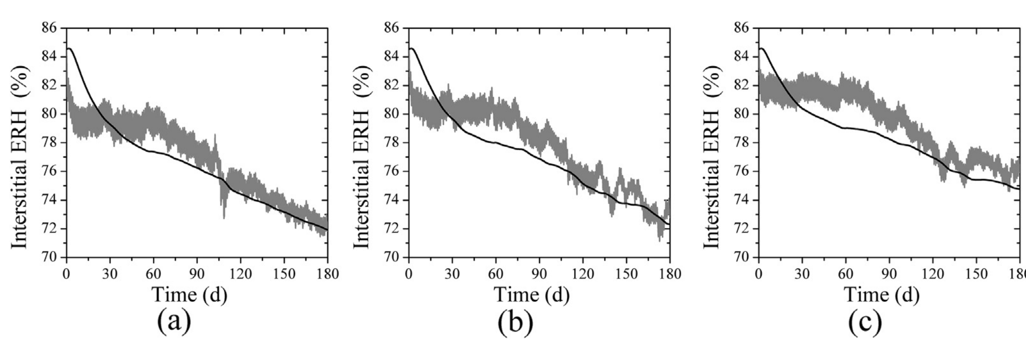

Fig. 9 – Equilibrium relative humidity (ERH) evolution at a) Balcarce, b) Pergamino and c) Saenz Peña. —, ERH at y = 0.8 m; —, ERH at y = 1.4 m. Bagging conditions: 16% w.b, 40 °C.

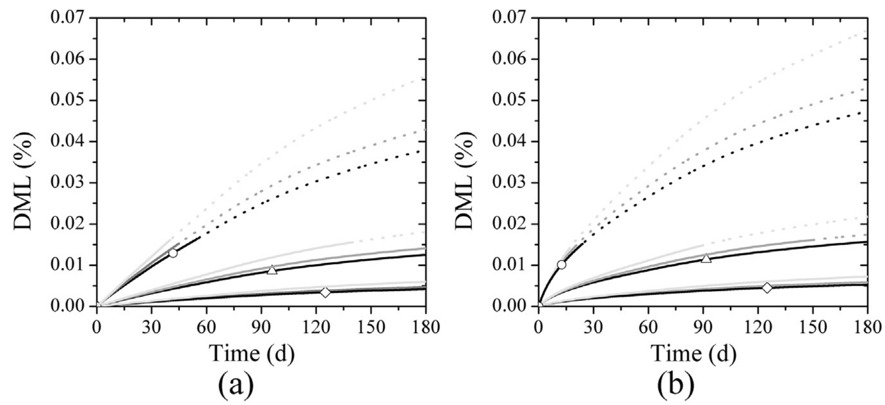

Fig. 10 – Dry matter loss (DML) in a silo-bag holding wheat at the three agricultural areas. Balcarce (—), Pergamino (—) and Saenz Peña (—). Bagging moisture content: 12% w.b (◇); 14% w.b (△) and 16% w.b (○). Bagging temperature: a) 25 °C; b) 40 °C.

Argentina. The time courses of grain temperature, MC, ERH and DML were also compared.

Results showed that reference levels of O_2 and CO_2 strongly depend on initial moisture content and bagging grain temperature. Also, climatic conditions produce significant changes, especially for dry and slightly wet grain. A difference of about 7 to 8 °C in mean ambient temperature between the northern (Saenz Peña) and southern location (Balcarce) shifts reference levels by about 2% V/V for 12% w.b and about 4% V/V for 14% w.b. At the three locations, O_2 depleted to less than 1% for 16% w.b.

The grain mean temperature in combination with CO_2 and O_2 levels achieved in the silo-bags demonstrated that, for the climatic conditions of the southern and central regions of Argentina, insect development would be very restricted. Storing dry grain in the northern regions (sub-tropical weather) might support insect activity during summer and autumn. A slight MC increase at the top grain layer was predicted by the model.

For wet grain, ERH at the top grain layer remained above safe levels even during the cold season, implying that mould development could be expected. However, predicted mean dry matter loss for all the storage conditions did not exceed limits that would result in reduction of the grain's commercial quality, although seed quality could be affected for wet storage conditions.

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