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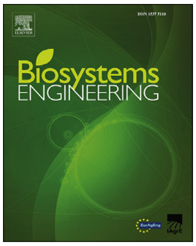

Research Paper

Validation of a heat, moisture and gas concentration transfer model for soybean (*Glycine max*) grains stored in plastic bags (silo bags)

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A two dimensional finite element model that predicts temperature distribution and moisture content of soybean stored in silo bags due to seasonal variation of climatic conditions is described. The model includes grain respiration and calculates carbon dioxide and oxygen concentrations during storage.

The model validation was carried out by comparing predicted temperature, moisture content and gas concentration with measured data in field tests. Overall, the model underpredicted grain temperatures. Mean absolute difference was 0.5–1 °C for the bottom and middle layers and about 1.5 °C for the top layer. A slight moisture increase (0.4% w.b. at most) was predicted for the top grain layer while moisture for the middle and bottom layers remained almost unchanged during the storage period.

A model of respiration rate of soybean as a function of temperature, moisture content and O_2 level was used to predicted gas concentrations in the interstitial air. Average CO_2 and O_2 concentrations were compared with measured data. As mean grain temperature was below 15 °C for most of the storage period, O_2 consumption and CO_2 production were low. O_2 level was about 19–20% V/V for dry soybean (13% w.b.) and about 16–17% V/V for wet soybean (15% w.b.). Predicted CO_2 concentration varied from 1% V/V for dry soybean (13% w.b.) to 2% V/V points for wet soybean (15% w.b.). Though CO_2 relative differences were high, the general trends of measured gas evolution were compatible with the simulated ones, indicating that the changes in CO_2 and O_2 concentrations during storage were satisfactorily predicted by use of the proposed correlations.

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Notation

x, y	Cartesian coordinates, m
c	specific heat capacity of grain bulk, J kg^{-1} K^{-1}
C_H, K_H, N	parameters of the modified Henderson equation, °C, °C^{-1}, dimensionless, respectively
CO_2	carbon dioxide concentration, % V/V
D_i	diffusivity of component i through air, m^2 s^{-1} (with i = w, CO_2 and O_2)
D_i^*	effective diffusivity of component i through intergranular 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	thermal conductivity, W m^{-1} K^{-1}
L	silo bag characteristic length, m
L_g	latent heat of vaporisation of moisture in the grain, J kg^{-1}
M	grain moisture content, % w.b.
M_i	molecular weight of component i, grams mol^{-1} (with i = CO_2 and O_2)
n	normal direction
O_2	oxygen concentration, % V/V
p_s	saturation pressure of water vapour, Pa
p_v	partial pressure of water vapour, Pa
p_{atm}	atmospheric pressure, 101,325 Pa
P_{CO_2}	equivalent permeability of CO_2 through plastic layer, m^3 m s^{-1} m^{-2} Pa^{-1}
P_{O_2}	equivalent permeability of O_2 through plastic layer, m^3 m s^{-1} m^{-2} Pa^{-1}
q_H	heat released in respiration, 14.766 J mg^{-1} [O_2]
q_w	water vapour produced in respiration, 5.62×10^{-7} kg [H_2O] mg^{-1} [O_2]
R_w	water vapour gas constant, 461.52 J kg^{-1} K^{-1}
R_g	universal gas constant, 8.314 J mol^{-1} K^{-1}
R	correlation coefficient
t	time, s
T_C	temperature, °C
T	absolute temperature, K
T_{Ci}	daily or annual soil temperature parameters, °C, $i = 1, 2$
V	bed of grain volume, m^3
W	grain moisture content, d.b.
Y_{CO_2}	rate of carbon dioxide production, mg [CO_2] kg^{-1} [dry matter] d^{-1}
Y_{O_2}	rate of oxygen consumption, mg [O_2] kg^{-1} [dry matter] d^{-1}
Y_{H_2O}	rate of water vapour production, mg [H_2O] kg^{-1} [dry matter] d^{-1}

Greek symbols

α	silo bag surface absorptivity
ε	porosity, fractional
φ	daily or annual phase angle
Γ	domain boundary
η	change in the partial pressure due to change in the moisture content at constant temperature, Pa
ρ	density, kg m^{-3}
ρ_{bs}	dry bulk density, kg [dry matter] m^{-3}
σ	Stefan–Boltzmann's constant, 5.6697×10^{-8} W m^{-2} K^{-4}
τ	tortuosity factor
ω	change in the partial pressure due to change in the temperature at constant moisture content, Pa K^{-1}
Ω	domain
ξ	emissivity
ψ	daily or annual angular frequency, s^{-1}

Subscripts

amb	ambient
b	bulk grain
g	grain
0	initial
sky	sky
soil	soil
w	water vapour

1. Introduction

During the last 10 years the overall grain production in Argentina increased by 50 Mt and soybean was the greatest contributor to this increase. Soybean has a major impact on the Argentina economy. Argentina is the third world producer (after the USA and Brazil) and exporter of soybean, the fourth world producer of soybean meal (after China, the USA and Brazil) and the largest exporter of soybean meal and soybean oil. The Argentine soybean chain is the most integrated in world trade: more than 90% of total production is destined for international markets (Ciani, 2016; Regunaga, 2010).

In Argentina during year 2014, around 200,000 "silo bags" were used to store more than 40% of the total grain production (107 Mt) (INTA Informa, 2014). Because of its economic implications (grain identity preservation, variety segregation, farm logistics, storage cost reduction, marketing benefits, etc.) and 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 with a wide range of weather conditions, from hot (e.g. Sudan and Brazil) to cold (e.g., Russia and Canada) (Bartosik, 2012).

This storage technique was originally used for grain silage, and is now used for storing dry grain in sealed plastic bags. The respiration process of the biological agents in the grain ecosystem (grain, insects, mites and microorganisms) increases carbon dioxide (CO_2) and reduces oxygen (O_2) concentrations. This modified atmosphere inhibits biotic activity, promoting a suitable environment for grain conservation (Navarro, Noyes, & Jayas, 2002, chap. 2).

Gas concentration depends on the balance between respiration of the ecosystem, the entrance of external O_2 to the system, and the loss of CO_2 to the ambient air. The transfer of