GROWTH CURVE FUNCTIONS IN MODELING THE THIN-LAYER DRYING OF CORN

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Abstract. Modeling the thin-layer drying process for corn is described using 37 growth curve functions. The most effective functions were qualified by the application of Akaike Information Criterion and Bayesian Information Criterion. Both criteria showed that the thin-layer drying process for corn was best described by the baroreflex five-parameter function.

Key words: Akaike Information Criterion, Bayesian Information Criterion, growth curve models, corn, modeling, R package

Introduction

Corn is one of the most important and widely used crops in the world. The moisture content of the harvested grain can reach values as high as 30-35% Polish climatic conditions. In order to preserve corn kernel quality, it is necessary to reduce the moisture content to approximately 14% by means of a drying process. Since drying costs can total as much as 40% of all direct costs, it is an operation which requires careful planning [Sulewska 2008]. Computer simulations of the drying process can prove useful in this respect. The objective of this paper is to analyze the possibility of implementing growth curve functions in using the R statistical platform [R Development Core Team 2009] to develop a model for the thin-layer drying process for corn. Such a model constitutes an important element of the overall drying model.

Materials and methods

The corn variety Clarica, produced by Pioneer company (FAO 280), was used for the experiment. It was provided for the research in two batches; each batch was gathered from a different part of the field. The corn moisture was measured indirectly by an electric hygrometer; the results were 28.7 and 25.9%, for batch 1 and batch 2, respectively.

The drying factor was air. The airflow velocity was 0.4 $m \cdot s^{-1}$ and the air temperature of the air was 40°C. The experiment was performed in five series, with five different values of relative humidity: 30, 35, 40, 45, and 50%. For the first three series, the corn samples were collected from the batch with the lower humidity; for the final two series, they were taken from the portion with the higher humidity. For every series, there were five repetitions of the experiment and the water content was measured at successive time steps for every sample. On this basis, the average value of the water content for every series was determined at successive time steps of the drying process. The details in regard to the experimental procedures are described by Kujawa [2009] and Weres et al. [2009].

Table 1. Growth curve functions used in the analysis

Function name	Description	Literature
baro5	baroreflex five-parameter function	Ricketts, Head 1999
BC.4, BC.5	Brain-Cousens modified log-logistic functions	Brain, Cousens 1989
CRS.4a, CRS.4b, CRS.4c	four-parameter Cedergreen-Ritz-Streibig modified log-logistic functions	Cedergreen et al. 2005
CRS.5a, CRS.5b, CRS.5c	five-parameter Cedergreen-Ritz-Streibig modified log-logistic functions	Cedergreen et al. 2005
CRS.6	six-parameter Cedergreen-Ritz-Streibig modified log-logistic function	Cedergreen et al. 2005
EXD.2, EXD.3	Exponential functions	Ritz, Streibig 2005
G.4	Gompertz growth function	Hunt 1982
L.3, L.4, L.5	logistic functions	Ritz, Streibig 2005
LL.2	two-parameter log-logistic function	Finney 1971
LL.3	three-parameter log-logistic function	Finney 1971
LL.3u	three-parameter logistic function where the upper limit is equal to 1	Finney 1971
LL.4	four-parameter log-logistic function	Seber, Wild 1989
LL.5	five-parameter log-logistic function	Finney 1979
LN.2, LN.3, LN.3u, LN.4	log-normal functions	Finney 1971, Bruce, Versteeg 1992
UCRS.4a, UCRS.4b, UCRS.4c	four-parameter Cedergreen-Ritz-Streibig modified log-logistic functions for describing u-shaped hormesis	Cedergreen et al. 2005
UCRS.5a, UCRS.5b, UCRS.5c	five-parameter Cedergreen-Ritz-Streibig modified log-logistic functions for describing u-shaped hormesis	Cedergreen et al. 2005
W1.2, W2.2	two-parameter Weibull functions	Seber, Wild 1989
W1.3, W2.3	three-parameter Weibull functions	Seber, Wild 1989
W1.4, W2.4	four-parameter Weibull functions	Seber, Wild 1989

The growth curve functions were used to model the corn-drying process. 37 growth curve functions were included in the analysis (Table 1). All the calculations were performed separately for every series. The main tool used was the R platform. Package 'drc'

[Ritz, Streibig 2005] was used for the estimation of parameters for every function based on nonlinear regression. The Akaike Information Criterion, AIC, [Akaike 1974] and Bayesian Information Criterion, BIC, [Schwarz 1978] were used for comparison of the functions being evaluated.

It should be mentioned that the authors' intention was not to replace the theoretical structural model of heat and mass transport [Pabis et al. 1998], but to propose an informative model that allows the representation of sets of data from corn drying experiments and the rapid and precise prediction of the process being analyzed.

Results

For modeling the corn drying process, 37 growth curve functions were used and, as the result, the parameters of these functions were estimated. The comparison of the functions was based on AIC and BIC. These are the two measures of how well the function fits the experimental data. The function with the lowest value of the AIC or BIC coefficient is deemed to be the most suitable. The results are ordered on the basis of the average values of the AIC and BIC coefficient respectively. In Tables 2 and 3, the calculated values of the average AIC and AIC coefficient for the five series are presented. In Tables 4 and 5, the calculated values of the BIC coefficient for five datasets are presented, as are the average BIC.

Table 2. AIC for the 10 best-fitted growth curve functions, after sorting

No	Function name	Average AIC	AIC				
			data 1 (30%)	data 2 (35%)	data 3 (40%)	Data 4 (45%)	Data 5 (50%)
1	baro5	-2889.20	-3050.91	-2926.71	-2890.80	-2748.82	-2828.76
2	W1.4	-2825.50	-2953.08	-2935.44	-2977.53	-2639.24	-2622.19
3	CRS.6	-2811.15	-2951.33	-2860.58	-2826.74	-2680.90	-2736.22
4	CRS.5b	-2779.45	-2952.98	-2861.15	-2813.87	-2631.97	-2637.29
5	LL.5	-2738.13	-2894.77	-2862.46	-2846.38	-2550.94	-2536.11
6	UCRS.5c	-2509.39	-2681.29	-2663.36	-2608.68	-2335.15	-2258.47
7	UCRS.5a	-2455.38	-2575.72	-2554.61	-2527.76	-2309.48	-2309.31
8	UCRS.5b	-2441.15	-2608.48	-2583.82	-2505.71	-2272.40	-2235.36
9	CRS.5c	-2440.89	-2564.33	-2559.12	-2463.78	-2304.19	-2313.03
10	CRS.4b	-2387.09	-2220.60	-2270.42	-2325.02	-2489.62	-2629.78

Table 3. AIC for the 10 worst-fitted growth curve functions, after sorting

No	Function name	Average AIC	AIC				
			data 1 (30%)	data 2 (35%)	data 3 (40%)	data 4 (45%)	Data 5 (50%)
1	LN.3u	-1904.12	-195558	-1970.02	-1931.39	-1806.05	-1857.56
2	G.4	-1895.90	-1795.72	-1783.63	-1840.89	-2015.08	-2044.19
3	LN.2	-1825.83	-1950.96	-1971.66	-1920.54	-1665.99	-1620.02
4	W2.4	-1825.57	-1861.30	-1879.31	-1840.79	-1749.76	-1796.68
5	W1.3	-1780.63	-1630.74	-1668.10	-1710.22	-1870.08	-2024.00
6	W1.2	-1695.47	-1527.14	-1562.94	-1608.88	-1812.78	-1965.63
7	W2.3	-1559.12	-1705.45	-1693.28	-1604.13	-1417.34	-1375.39
8	W2.2	-1311.78	-1439.36	-1427.65	-1353.50	-1182.20	-1156.21
9	EXD.2	-1120.22	-972.62	-985.56	-1039.95	-1250.52	-1352.44
10	L.3	-1098.32	-956.21	-968.95	-1021.57	-1227.12	-1317.76

Table 4. BIC for the 10 best-fitted growth curve functions, after sorting

No	Function name	Average BIC	BIC				
			data 1 (30%)	data 2 (35%)	data 3 (40%)	data 4 (45%)	Data 5 (50%)
1	baro5	-2867.22	-3028.93	-2904.73	-2868.83	-2726.84	-2806.78
2	W1.4	-2807.18	-2934.77	-2917.12	-2959.22	-2620.92	-2603.88
3	CRS.6	-2785.51	-2925.69	-2834.94	-2801.10	-2655.26	-2710.58
4	CRS.5b	-2757.47	-2931.00	-2839.18	-2791.89	-2609.99	-2615.31
5	LL.5	-2716.16	-2872.80	-2840.48	-2824.40	-2528.96	-2514.13
6	UCRS.5c	-2487.41	-2659.31	-2641.38	-2586.70	-2313.17	-2236.49
7	UCRS.5a	-2433.40	-2553.74	-2532.63	-2505.78	-2287.51	-2287.33
8	UCRS.5b	-2419.18	-2586.50	-2561.84	-2483.73	-2250.42	-2213.39
9	CRS.5c	-2418.91	-2542.36	-2537.14	-2441.80	-2282.21	-2291.05
10	CRS.4b	-2368.77	-2202.29	-2252.11	-2306.70	-2471.31	-2611.47

Table 5. BIC for the 10 worst-fitted growth curve functions, after sorting.

No	Function name	Average BIC	BIC				
			data 1 (30%)	data 2 (35%)	data 3 (40%)	data 4 (45%)	Data 5 (50%)
1	LN.3u	-1889.47	-1940.93	-1955.37	-1916.74	-1791.40	-1842.91
2	G.4	-1877.59	-1777.40	-1765.31	-1822.58	-1996.77	-2025.88
3	LN.2	-1814.85	-1939.97	-1960.67	-1909.55	-1655.00	-1609.03
4	W2.4	-1807.25	-1842.98	-1861.00	-1822.48	-1731.45	-1778.36
5	W1.3	-1765.97	-1616.09	-1653.45	-1695.56	-1855.43	-2009.34
6	W1.2	-1684.48	-1516.15	-1551.95	-1597.89	-1801.79	-1954.64
7	W2.3	-1544.46	-1690.79	-1678.63	-1589.47	-1402.69	-1360.74
8	W2.2	-1300.79	-1428.37	-1416.66	-1342.51	-1171.21	-1145.22
9	EXD.2	-1109.23	-961.63	-974.57	-1028.96	-1239.53	-1341.45
10	L.3	-1083.67	-941.56	-954.30	-1006.92	-1212.47	-1303.11

In the second column of Tables 2-5. the names of functions from 'drc' are used. The calculations of AIC and BIC reveal some order of how well the functions fit the data.

The best results for both the average values of the coefficients and the separate values for each series were obtained for the baroreflex function with 5 parameters. This function has the following form (1-2):

$$f(t) = c + \frac{d-c}{1 + g\exp\{a(\log(t) - \log(e))\} + (1-g)\exp\{b(\log(t) - \log(e))\}} \quad (1)$$

$$g = \frac{1}{1 + \exp\{\frac{2ab}{|a+b|}(\log(t) - \log(e))\}} \quad (2)$$

The estimated parameters for the baroreflex function are presented in Table 6.

Table 6. Values of parameters for the baroreflex function for each series

Parameter	Data 1	Data 2	Data 3	Data 4	Data 5
A	0.9066	0.9004	0.9102	0.9220	0.9335
B	1.3385	1.3164	1.3581	1.4814	1.4782
C	0.0757	0.0716	0.0548	0.0238	0.0124
D	1.0008	1.0005	1.0019	1.0020	1.0046
E	3.8023	3.9171	4.0524	4.6288	5.2972

On the basis of these results, we can visualize the fit of the baroreflex function to the data (Fig. 1).

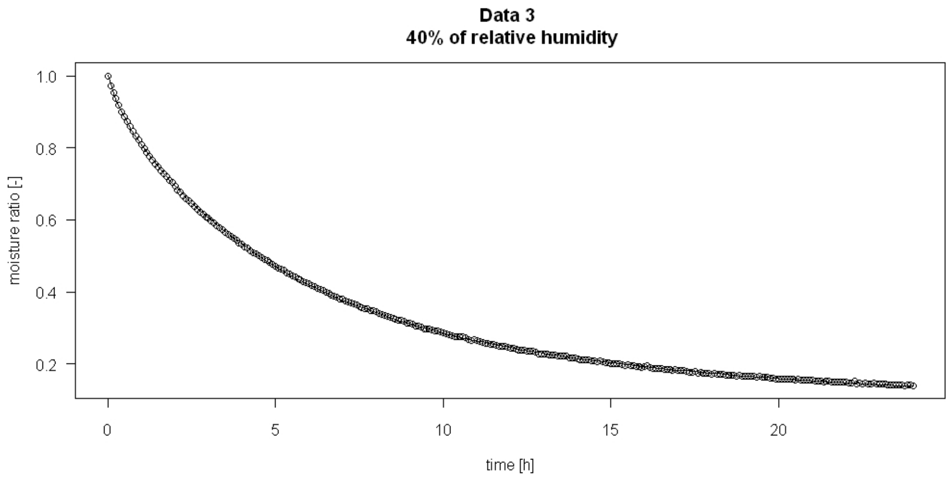

Fig. 1. Plot of the baroreflex function fit to one series of data

Discussion

To illustrate how the drying process occurs over time, we used several growth curve functions including: exponential, Gompertz, logistic, modified logistic, log-logistic, modified log-logistic, log-normal and Weibull. The AIC and BIC criteria show each of these models and depict how well each of them fits to the five series of data. On scrutinizing Table 2, it becomes evident that the ten different models satisfactorily predict the gradual loss of water in corn kernels. Given that drying is an expensive process, it is worth keeping it under control. Our research indicates functions that match best for these data type and which should be used to represent empirical data in such experiments. It is noteworthy that the function which best fits all five series of data together is also best for each of them separately.

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KRZYWE WZROSTU W MODELOWANIU PROCESU SUSZENIA KUKURYDZY W CIENKIEJ WARSTWIE

Streszczenie: Modelowanie procesu suszenia kukurydzy w cienkiej warstwie zostało opisane przy użyciu 37 krzywych wzrostu. Najlepiej dopasowane krzywe zostały wyłonione w oparciu o Informacyjne Kryterium Akaike oraz Bayesowkie Kryterium Informacyjne Schwarza. Oba współczynniki pokazały, iż proces suszenia kukurydzy w cienkiej warstwie najlepiej odwzorowuje pięcioparametrowa krzywa baroreflex.

Słowa kluczowe: Informacyjne Kryterium Akaike, Bayesowkie Kryterium Informacyjne Schwarza, krzywe wzrostu, kukurydza, modelowanie, R

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