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Testing a bell-shaped function for estimation of fully expanded leaf area in modern maize under potential production conditions

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ABSTRACT

Accurate leaf area simulation is critical for the performance of crop growth models. Area of fully expanded individual leaves of maize hybrids released before 1995 (defined as old hybrids) has been simulated using a bell-shaped function (BSF) and the relationship between its parameters and total leaf number (TLNO). However, modern high-yielding maize hybrids show different canopy architectures. The function parameters calibrated for old hybrids will not accurately represent modern hybrids. In this study, we evaluated these functions using a dataset including old and modern hybrids that have been widely planted in China in recent years. Maximum individual leaf area (Y_0) and corresponding leaf position (X_0) were not predicted well by TLNO (R^2 = 0.56 and R^2 = 0.70) for modern hybrids. Using recalibrated shape parameters *a* and *b* with values of Y_0 and X_0 for modern hybrids, the BSF accurately predicted individual leaf area (R^2 = 0.95–0.99) and total leaf area of modern hybrids (R^2 = 0.98). The results show that the BSF is still a robust way to predict the fully expanded leaf area of maize when parameters *a* and *b* are modified and Y_0 and X_0 are fitted. Breeding programs have led to increases in TLNO of maize but have not altered Y_0 and X_0, reducing the correlation between Y_0, X_0, and TLNO. For modern hybrids, the values of Y_0 and X_0 are hybrid-specific. Modern hybrids tend to have less-negative values of parameter *a* and more-positive values of parameter *b* in the leaf profile. Growth conditions, such as plant density and environmental conditions, also affect the fully expanded leaf area but were not considered in the original published equations. Thus, further research is needed to accurately estimate values of Y_0 and X_0 of individual modern hybrids to improve simulation of maize leaf area in crop growth models.

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Table 1 – Principal equations used for estimation of fully expanded leaf area in maize. Y_0 is the area of the largest leaf, X_0 is the position of the largest leaf, a and b are dimensionless empirical constants.

Equation number	Equation	Reference
Bell-shaped function (Eq. (1)) and its modifications (Eqs. (2) and (3))		
1	$LA_n = Y_0 \times \exp.[a \times (X_n - X_0)^2 + b \times (X_n - X_0)^3]$	Dwyer and Stewart [1]
2	$LA_n = Y_0 \times \exp.[a \times (X_n / X_0 - 1)^2 + b \times (X_n / X_0 - 1)^3]$	Dwyer et al. [5]
3	$LA_n = Y_0 \times \exp.\{a \times [(X_n - X_0) / (X_0 - 1)]^2 + b \times [(X_n - X_0) / (X_0 - 1)]^3\}$	Lizaso et al. [8]
Relationships between Y_0, X_0, a, b, and TLNO		
4	$Y_0 = -235 + 62 \times \text{TLNO}$, $R^2 = 0.94$	Keating and Wafula [9]
5	$X_0 = 2.42 + 0.575 \times \text{TLNO}$, $R^2 = 0.99$	Keating and Wafula [9]
6	$a = -0.0183 + 0.0146 / (1 - 0.0966 \times \text{TLNO})$, $R^2 = 0.99$	Keating and Wafula [9]
7	$b = 0.0004 + 0.00037 / (1 - 0.0883 \times \text{TLNO})$, $R^2 = 0.98$	Keating and Wafula [9]
Modified relationships between Y_0, X_0, a, b, and TLNO		
8	$Y_0 = 1000 \times \exp.[(-1.17 \pm 0.015) + 0.047 (\pm 0.006) \times \text{TLNO}]$ ($R^2 = 0.82$, $n = 18$)	Birch et al. [10]
9	$X_0 = 0.67 (\pm 0.01) \times \text{TLNO}$ ($R^2 = 0.99$, $n = 11$)	Birch et al. [10]
10	$a = -0.009 (\pm 0.004) - \exp.[-0.20 (\pm 0.007) \times \text{TLNO}]$ ($R^2 = 0.95$, $n = 12$)	Birch et al. [10]
11	$b = 0.0006 (\pm 0.002) - \exp.[-0.43 (\pm 0.008) \times \text{TLNO}]$ ($R^2 = 0.91$, $n = 12$)	Birch et al. [10]

1. Introduction

Accurate simulation of leaf area is critical for crop growth models [1, 2]. Two approaches based on leaf number have been used to simulate the area of fully expanded individual leaves of maize in previous studies [1, 3–5]. In the first approach, fully expanded leaf area is simulated using four discrete equations for leaves 1–3, 4–11, 12 to TLNO-4, and TLNO-3 to TLNO [3]. However, the area of leaves above the 12th leaf is often underestimated by this function, especially for high-yielding modern maize hybrids [6, 7].

The second approach is independently described by three equations (Eqs. (1)–(3), Table 1). The parameters in these equations are typically fitted to measured field data and have shown in previous studies to give good predictions of leaf area for a range of hybrids growing in different soils [1, 5, 8]. Keating and Wafula found that the values of parameters Y_0, X_0, a, and b can be estimated from TLNO (Eqs. (4)–(7), Table 1). The BSF (Eq. (1), Table 1) used with parameters estimated by Eqs. (4)–(7) gave good predictions of individual leaf area and total leaf area of maize grown in moderate temperature regions with a low plant population of 2.2 plants m^{-2} [9].

Birch et al. [10] modified the relationships between TLNO and the four parameters using five maize hybrids grown in subtropical conditions with a plant density of 7 plants m^{-2} (southeastern Queensland, Australia) (Eqs. (8)–(11), Table 1). The model simulated leaf area well under the optimal temperature for leaf expansion. However, validation using an independent data set was not performed [10]. Elings [11] calibrated Eqs. (4)–(7) (Table 1) for tropical cultivars growing under tropical conditions at various water and nitrogen levels at a plant density of 5.33 plants m^{-2}. However, coefficients of determination (R^2) were too low to justify estimation of function parameters from TLNO. It is likely that leaf expansion was reduced by limitations imposed by water, N and temperature [11–13].

In previous studies, calibrations of the BSF and its parameters have used older maize hybrids released before 1995 and grown at low plant densities [9–11]. Because newer high-yielding maize hybrids have different canopy architecture that is sensitive to plant density and environmental condition, it is expected that function parameters calibrated for old hybrids will not accurately represent modern hybrids. The objective of this study was to calibrate and evaluate the BSF and its parameters for modern hybrids, and to develop a generalized method to estimate individual leaf area and total leaf area for a wide range of hybrids differing in total leaf number grown in different locations and environmental conditions without nutrient or water stress.

2. Materials and methods

2.1. *Experimental site and design*

Two experiments were conducted to collect leaf area data for modern maize hybrids for model calibration (Table 2). The first experiment (experiment 1) was conducted at the Quzhou Experiment Station, Hebei province, China (36°52′N, 115°02′E). Maize (cv. Zhengdan 958) was sown at a density of 7.5 plants m^{-2}. There were three phosphorus (P) levels with four replicates in a randomized complete block, including P_0 (no P application), P_{75} (75 kg P_2O_5 ha^{-1}), and P_{300} (300 kg P_2O_5 ha^{-1}) as superphosphate, but all leaf area data were collected from treatments P_{75} and P_{300}, which provided sufficient P to the crop. Overall fertilizer applications were high enough so that N, P, or K deficiencies would not limit maize growth, based on previous results. Irrigation was applied to ensure no water stress during the growing season.

The second experiment (experiment 2) was conducted at Lishu county, Jilin province, China (43°21′N, 124°04′E). Six hybrids commonly grown in northeast China were evaluated to measure leaf expansion. All treatments were replicated three times in a randomized complete block design. Rainfall was 736 mm during the growing season in 2016, an amount much higher than the evapotranspiration of maize production in this area and ensuring that water demand was met. All field experiments were rigorously controlled for pests and diseases.

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