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Optimal Nitrogen Fertilization to Reach the Maximum Grain and Stover Yields of Maize (*Zea mays* L.): Tendency Modeling

Sergio E. Medina-Cuéllar [1], Deli N. Tirado-González [2,*], Marcos Portillo-Vázquez [3], Sergio Orozco-Cirilo [4], Marco A. López-Santiago [5], Juan M. Vargas-Canales [4], Carlos A. Medina-Flores [6] and Abdelfattah Z. M. Salem [7]

1 Departamento de Arte y Empresa, División de Ingenierías Campus Irapuato-Salamanca, Universidad de Guanajuato, Carretera Salamanca-Valle de Santiago km 3.5 + 1.8, Salamanca 36885, Mexico; se.medina@ugto.mx
2 Centro Nacional de Investigación Disciplinaria Agricultura Familiar (CENID AF), Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP), Carretera Lagos de Moreno-Jalisco km 8.5, Ojuelos de Jalisco 47540, Mexico
3 Coordinación de Posgrado, División de Ciencias Económico Administrativas, Universidad Autónoma Chapingo, Carretera México–Texcoco km 38.5, Texcoco 56230, Mexico; mportillo49@yahoo.com.mx
4 Departamento de Estudios Sociales, División de Ciencias Sociales y Administrativas, Universidad de Guanajuato. Av. Ing. Javier Barros Sierra No. 201, Ejido Santa María del Refugio, Celaya 38110, Mexico; orozcosergio@ugto.mx (S.O.-C.); jm.vargas@ugto.mx (J.M.V.-C.)
5 Unidad Regional Universitaria de Zonas Áridas, Universidad Autónoma Chapingo, Carretera Gómez Palacio–Chihuahua km 40, Bermejillo, Durango 35230, Mexico; marco-andres@chapingo.uruza.edu.mx
6 Unidad Académica de Medicina Veterinaria y Zootecnia, Universidad Autónoma de Zacatecas, Carretera Panamericana Zacatecas-Fresnillo km 31.5, Enrique Estrada 98500, Mexico; carlosmedina@uaz.edu.mx
7 Facultad de Medicina Veterinaria y Zootecnia, Universidad Autónoma del Estado de Mexico, El Cerrillo Piedras Blancas, Toluca 50295, Mexico; salem@uaemex.mx
* Correspondence: tirado.deli@inifap.gob.mx

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Abstract: Utilization of maize stover to the production of meat and milk and saving the grains for human consumption would be one strategy for the optimal usage of resources. Variance and tendency analyses were applied to find the optimal nitrogen (N) fertilization dose (0, 100, 145, 190, 240, and 290 kg/ha) for forage (F), stover (S), cob (C), and grain (G) yields, as well as the optimal grain-to-forage, cob-to-forage, and cob-to-stover ratios (G:F, C:F, and C:S, respectively). The study was performed in central Mexico (20.691389° N and −101.259722° W, 1740 m a.m.s.l.; Cwa (Köppen), 699 mm annual precipitation; alluvial soils). N-190 and N-240 improved the individual yields and ratios the most. Linear and quadratic models for CDM, GDM, and G:F ratio had coefficients of determination (R^2) of 0.20–0.46 ($p < 0.03$). Cubic showed R^2 = 0.30–0.72 ($p < 0.02$), and the best models were for CDM, GDM, and the G:F, C:F, and C:S DM ratios (R^2 = 0.60–0.72; $p < 0.0002$). Neither SHB nor SDM negatively correlated with CDM or GDM (r = 0.23–0.48; $p < 0.0001$). Excess of N had negative effects on forage, stover, cobs, and grains yields, but optimal N fertilization increased the proportion of the G:F, C:F, and C:S ratios, as well as the SHB and SDM yields, without negative effects on grain production.

Keywords: maize hybrid; nitrogen fertilization; tendency models; grain yield; grain-to-stover ratio

1. Introduction

Due to climate change, caused by the release of greenhouse gases (GHG), in part caused by crops and livestock [1–3], the increment in temperatures and changes in precipitation patterns might reduce the potential yields and nutrient availability of crops and grasslands [4,5]. Furthermore, increasing demand for land and a reduction in the amount and quality of spaces to produce grains for humans and forage for livestock are factors threatening food security [6].

The efficiency of agricultural and livestock production plays an important role in social and economic development. According to the FAO [7], maize is one of the world's most widely cultivated crop, and one of the most important crops for world food security, used to feed humans and livestock.

Utilization of maize stover in the production of meat and milk and saving the grains for human consumption would be one strategy for the optimal usage of resources [8]. Increasing the grain and stover individual yields and quality, and on the other side, the improvement of the starch:cell wall (neutral detergent fiber (NDF)) ratio of whole maize plants would be an alternative to use higher amounts of forage in ruminant diets [9,10].

N deficiencies reduce the leaf area and the radiation interception, primarily decreasing the photosynthetic rate per unit area, affecting the final grain composition and yield [11]. N fertilization can improve the yield and composition of maize grains and stalks [8,12,13], such as the total crude protein (CP) proportion in grains to feed humans, but is also inversely related to the NDFs [8,14], which might have a positive effect on the degradability and CP availability of forages, and therefore on milk and meat production [10,15–18]. An increase in CP might not be negatively related to the grain and forage yields [19,20].

However, excessive application of N fertilizer has negative effects on crops, greatly reduces N-use efficiency, and causes significant nitrate leaching losses [11], contributing to GHG since it is the major source of nitrous oxide (N_2O) [3]. Therefore, N must be applied at rates that satisfy both economic and environmental objectives and is critical for sustainable agriculture [21].

Optimal fertilization is when the maximum yield: average N fertilization ratio is reached (maximum yield conversion). The forage and grain yield increments show two different economical processes: at first, the average yield reach a maximum when a linear trend is observed from the origin to inflection point, after the tangent represents a reduction in the yield: N fertilization ratio [22]. Tendency models are useful to describe dose–response phenomena; in biological processes, quadratic and cubic models can find the inflection points of optimal values and discriminate between the sub or over doses [10,18].

The present study had the objective of testing the effects of different N fertilization doses on maize's forage, stover, cob, and grain HB and DM yields, and the proportions of the C:F, C:S, and G:F ratios, analyzing the relationships between those variables. Aside from this, we obtained linear, quadratic, and cubic models to find the optimal N doses to reach the maximum grain and stover productions, and the best C:F, C:S, and G:F ratios.

2. Materials and Methods

2.1. The Study Area

The experiment was performed in a zone in North-Central Mexico (20.691389° N and −101.259722° W; 1740 m above sea level), where the weather has been classified as monsoon-influenced humid subtropical (Cwa; Köppen classification), and the soil as primarily alluvial (48.1%) (vertisol (71.6%), phaeozem (11.2%), and cambisol (4.9%)). The average temperature and precipitation were 19.9 °C and 699 mm (rain mainly occurs during the summer).

2.2. Biological Material

The N fertilization doses were evaluated in an intermediate/early corn hybrid A-7573 (Asgrow® (Semillas y Agroproductos Monsanto, S.A. de C.V., Mexico)), which could produce white and yellow grains. The hybrid A-7573 is bred from a triple cross of lines adapted to spring and summer environmental conditions; the optimal crop density averages from 80,000 to 110,000 plants/ha, with minimal corn lodging.

2.3. Treatments and Crop Management

Crops were evaluated two times (15 May and 1 July) in three consecutive years (2018 to 2020) in two parcels located in the same region. Each treatment was randomly assigned to plots (30 × 16 m) nested into blocks (32 × 68 m) located in the parcel (128 × 84 m; 0.82 ha), considering the variability in topography, hydrology (the flow of water), and the sun's direction, divided by irrigation canals. The distance between rows was 50 cm, and the space among plants was 20 cm; the final crop density was 83,932 plants/h. A traditional soil management system was used (manual and minimum tillage). The scrubs were manually eliminated after being sowed.

Table 1 shows the evaluated N fertilization doses (treatments). Doses of 0, 2.50, 3.75, 5, 6.25, and 7.50 g of urea/plant were individually weighed and manually added in the base of each plant 5 cm beneath the soil, according to Wang and Xing [20,23] and Wang et al. [24], respectively. Half of the urea doses were applied on cultures at sowing time (0 d), and the rest 35 d after. Crops were not fertilized with phosphorous nor potassium (P, K).

Table 1. Nitrogen doses of fertilization added per hectare and per plant.

N-Doses	N (kg/ha)	Urea (kg/ha)	Urea (g)/Plant
Control	0	0	0
N-100	97	210	2.50
N-145	145	315	3.75
N-190	193	420	5.00
N-240	241	525	6.25
N-290	290	630	7.50

N-Dose, nitrogen doses: Control (0), 100, 145, 190, 240, and 290 kg/ha.

2.4. Evaluated Variables

Time to masculine and feminine inflorescences (tassel and ears) was registered from the sowing time to the moment when 50% of plants had pollen; 117 d after sowing (when grains showed $\frac{1}{2}$ of the milk line) [25], 10 plants per block were randomly selected and harvested. The number of cobs per plant were counted (C/plant).

Whole plants (forage (F)) were sectioned into stalks and leaves (stover (S)), cobs (C), and grain (G) and weighed, and then the plants' parts were collocated into a forced-air oven (Felisa®, FE-292 AD, Mexico) at 65 °C until reaching a constant weight (dry matter (DM)).

Data of the weights of the forage, stover, cobs, and grain in humid base (HB) (FHB, SHB, CHB, and GHB, respectively), and after being dried (DM) (FDM, SDM, CDM, and GDM, respectively) were included in the data bases. In addition, the grain-to-forage, cob-to-forage, and cob-to-stover ratios (G:F, C:F, and C:S ratios, respectively) were calculated for further analysis.

2.5. Statistical Analysis

2.5.1. Experimental Design and Variance Analysis (ANOVA)

The experiment was established in two parcels and carried out at different times (two times in three consecutive years (runs)) where treatments were randomly assigned using a block design (4 blocks per treatment). In addition, 10 sites (sub-runs) were randomly sampled into each block. Statistical analysis was performed using ANOVA, considering the fixed effects of the N doses and the random effects of runs nested into the parcels, and sub-runs nested into the blocks, including the initial weight of the complete plants and cobs (PW and CW) as covariates, according Models 1 and 2.

Statistical analysis was performed using the SAS software [26], and the determination and variation coefficients (R^2 and VC) were obtained using a lineal general modeling procedure (Proc GLM), and the statistical significances of the fixed and random effects were obtained using a mixed procedure (Proc Mixed).

Model 1

$$Y = \mu + \text{Run(Parcel)}_{ij} + \text{Trat}_k + \beta_{(x-x1)} + \varepsilon_{ijk} \quad (1)$$

where Y = C/Plant, FHB, SHB, CHB, GHB, FDM, CDM, GDM, C:F ratio, C:S ratio, and G:F ratio; Run(Parcel)_{Ij} = the random effect of the i^{th} run nested into the j^{th} parcel; Trat_k = the fixed effect of the k^{th} N dose of fertilization; $\beta_{(x-x1)}$ = covariates (PW and CW); and ε_{ijk}= random error.

Model 2

$$Y = \mu + \text{Sub-run(Block)}_{ij} + \text{Trat}_k + \beta_{(x-x1)} + \varepsilon_{ij} \quad (2)$$

where Y = C/Plant, FHB, SHB, CHB, GHB, FDM, CDM, GDM, C:F ratio, C:S ratio, and G:F ratio; Sub-run(Block)$_{ij}$ = the random effect of the ith sub-run nested into the jth block; Trat$_k$ = the fixed effect of the kth N dose of fertilization; $\beta_{(x-x1)}$ = covariates (PW and CW); and ε_{ijk} = random error.

2.5.2. Means Comparison

Adjusted means were obtained with the LsMeans instruction, and the least significant difference (LSD) was calculated using the standard errors (SE) obtained with the instruction/pdiff.

2.5.3. Pearson's Correlation, Trend Analysis, and Regression Models

Individual simple correlations (r) between variables were tested using Proc Corr [26]. Linear, quadratic, and cubic effects were assayed through orthogonal polynomial tests using the statistical software Paquete de la Universidad de Nuevo León [27]. The parameters for the linear, quadratic, and cubic functions were obtained using Proc Reg and Proc NLin [26].

2.5.4. Selection and Validity of the Models of the Categorical and Continuous Variables

In addition to the probability values (*p*-values (Fischer and T-student)) and R^2, Bayesian (BIC) and Akaike (AIC) criteria were used to select and validate the models.

3. Results

The crop was harvested when the forage and grains' DM were 22.48 ± 2.5 g/100 g and 40.88 ± 8.16 g/100 g.

3.1. Inflorescences and Humid Base Yields

Table 2 shows the masculine and feminine inflorescences, and the ANOVA did not show differences among the N doses ($p > 0.44$); however, those variables showed quadratic and cubic trends with N fertilization ($p < 0.0001$).

Table 2. Days to reach masculine and feminine inflorescences.

N-Doses	Masculine Inflorescences (d)	Feminine Inflorescences (d)
Control	64.50	65.50
N-100	64.50	66.00
N-145	63.75	64.50
N-190	65.50	66.75
N-240	63.75	64.50
N-290	64.50	65.75
R^2	0.67	0.71
VC (%)	1.99	3.85
p-value		
N-Dose	0.437	0.783
Trends		
Lineal	0.841	<0.0001
Quadratic	<0.0001	<0.0001
Cubic	<0.0001	<0.0001

N-dose, nitrogen fertilization: Control (0), 100, 145, 190, 240, and 290 kg/ha; R^2, coefficient of determination; VC, variation coefficient.

Treatments N-190 had the latest masculine and feminine inflorescences (65.50 vs. 64.50, and 66.75 vs. 65.50 d, control vs. N-190).

There were no differences among the N doses for C/plant and CHB (Table 3; $p > 0.26$), but both variables showed cubic trends, with the maximum values with N-100 (1.04 vs. 1.07, control vs. N-100) and N-240 (31.46 vs. 30.78 t/ha, control vs. N-240) ($p < 0.0001$).

Table 3. Whole plant, cobs, and grain humid base (HB) yields (t/ha).

N-Doses	C/Plant	SHB	FHB	CHB	GHB	C:F ratio	G:F Ratio	C:S Ratio
Control	1.04	81.55ab	112.28b	30.78	22.51ab	0.28ab	0.20cd	0.39ab
N-100	1.07	79.37cd	111.66e	29.88	22.43ab	0.27ab	0.20bcd	0.37ab
N-145	1.01	84.31a	115.47a	29.46	21.61b	0.27b	0.19d	0.36b
N-190	1.04	81.29bc	111.08c	30.78	24.01a	0.28ab	0.22a	0.39ab
N-240	1.03	80.52c	109.3d	31.46	23.45a	0.29a	0.21abc	0.40a
N-290	1.00	77.45d	108.13f	31.11	23.79a	0.29a	0.21abc	0.40a
R^2	0.45	0.96	0.99	0.64	0.63	0.37	0.42	0.35
VC (%)	14.14	3.95	10.65	10.99	11.74	9.93	10.7	13.93
p-value								
N-Doses	0.59	<0.0001	<0.0001	0.261	<0.0001	0.01	0.002	0.01
LSD (0.05) =	0.11	2.01	1.98	2.01	0.86	0.017	0.014	0.033
Trends								
Lineal	<0.0001	0.55	0.695	<0.0001	0.012	0.013	<0.0001	<0.0001
Quadratic	0.535	<0.0001	<0.0001	<0.0001	0.609	0.244	0.05	0.384
Cubic	<0.0001	<0.0001	<0.0001	<0.0001	0.189	0.55	0.03	0.421

Different letters represent significantly different means; N-doses, nitrogen fertilization: Control (0), 100, 145, 190, 240, and 290 kg/ha; HB, humid base; C/Plant, cobs per plant; SHB, stover yield; FHB, forage yield; CHB, cob yields; GHB, grain yields; C:F, cobs-to-forage; G:F, grain-to-forage; C:S, cobs-to-stover; R^2, coefficient of determination; VC, variation coefficient; LSD, least significant difference.

GHB was linearly improved with N fertilization but the best yield was obtained with N-190 (22.51 vs. 24.01 t/ha, control vs. N.190) ($p < 0.01$). The best production of FHB and SHB was reached with N-145 (81.55 vs. 84.31, and 112.28 vs. 115.47 t/ha, control vs. N-145) ($p < 0.0001$), showing quadratic and cubic trends ($p < 0.0001$).

The ratios C:F and C:S were affected by N fertilization, and were improved when doses over 190 kg/ha were applied to the crops (0.28 vs. 0.29, and 0.30 vs. 0.40, control vs. N-240) ($p < 0.01$); the G:F ratio also showed quadratic and cubic effects, suggesting an inflection point at N-190 (0.20 vs. 22, control vs. N-190) ($p < 0.05$).

3.2. Dry Matter Yields

The DM yields of forage, stover, cobs, and grain were affected by N dose ($p < 0.01$; Table 4). FDM and SDM had the best yields when N-240 was used in crops (30.65 vs. 32.17, and 18.51 vs. 19.68 t/ha, control vs. N-240), and CDM and GDM when N-190 was added (12.31 vs. 13.12, and 9 vs. 10.26 t/ha, control vs. N-190); in addition, N fertilization affected the ratios C:F, G:F, and C:S, which had the best means when N-190 was added (0.40 vs. 0.44, 0.30 vs. 0.35, and 0.68 vs. 0.81, control vs. N-190, respectively) ($p < 0.003$). All DM yields and ratios showed quadratic and cubic trends ($p < 0.0001$).

3.3. Linear, Quadratic, and Cubic Models

The R^2 coefficients were higher in the cubic models than in the linear and quadratic models (Table 5). There were significant linear models for the FHB, GHB, SHB, CDM, GDM, and G:F HB and DM ratios ($p < 0.01$), whose R^2 varied from 0.17 to 0.38. Quadratic models of FHB, CDM, GDM, SDM, G:F (HB and DM), C:S HB, and C:F HB showed R^2 values from 0.23 to 0.46 ($p < 0.03$). Except for C/Plant, SHB, and GHB, the cubic models for the rest of variables were significant ($p < 0.02$), with R^2 values from 0.30 to 0.72; however, the highest R^2 models were observed for CDM, GDM, and the G:F, C:F, and C:S DM ratios, whose R^2 values varied from 0.60 to 0.72 ($p < 0.0002$).

Table 4. Whole plant, cobs, and grain dry matter (DM) yields (t/ha).

N-Doses	FDM	SDM	CDM	GDM	C:F Ratio	G:F Ratio	C:S Ratio
Control	30.65b	18.51ab	12.31b	9.00c	0.40bc	0.30b	0.68bc
N-100	31.04b	18.85ab	12.69ab	9.56b	0.40bc	0.30b	0.68bc
N-145	30.24b	18.78ab	12.13b	8.90c	0.38c	0.29b	0.63c
N-190	29.78b	16.76c	13.12a	10.26a	0.44a	0.35a	0.81a
N-240	32.17a	19.68a	12.33b	9.17bc	0.39bc	0.29b	0.66bc
N-290	29.86b	17.54bc	12.30b	9.40bc	0.42ab	0.33ab	0.74ab
R^2	0.76	0.62	0.77	0.7	0.3	0.29	0.29
VC (%)	8.83	14.03	10.56	12.95	12.76	14.5	20.91
p-value							
N-Doses	0.005	0.001	0.01	0.001	0.006	0.0001	0.003
LSD (0.05) =	1.42	1.36	0.7	0.65	0.31	0.03	0.09
Trends							
Lineal	0.589	<0.0001	0.677	0.096	0.58	0.32	0.04
Quadratic	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Cubic	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Different letters are significant different means; N-doses, nitrogen fertilization: Control (0), 100, 145, 190, 240, and 290 kg/ha; DM, dry matter; SDM, stover yield; FMD, forage yield; CDM, cob yields; GDM, grain yields; C:F, cobs-to-forage; G:F, grain-to-forage; C:S, cobs-to-stover; R^2, coefficient of determination; VC, variation coefficient; LSD, least significant difference.

Table 5. Linear, quadratic, and cubic models for forage, stover, cob, and grains humid base (HB) and dry matter (DM) yields.

Variable (Y_i)	Trend			*p*-Value	R^2
	Linear: $Y_i = \beta_0 + \beta_1 X_i + \varepsilon_i$				
	β_0	β_1			
C/plant	1.13	−0.0006		0.09	0.10
FHB	113.47	−0.012		0.004	0.26
CHB	30.48	0.001		0.03	0.17
GHB	22.38	0.004		0.74	0.05
SHB	82.99	−0.013		0.004	0.26
G:F ratio HB	0.197	0.00007		0.05	0.20
C:S ratio HB	0.37	0.0001		0.07	0.11
C:F ratio HB	0.27	0.00005		0.07	0.12
CDM	12.42	0.0007		0.0003	0.38
GDM	9.13	0.002		0.007	0.24
SDM	18.99	−0.004		0.35	0.03
G:F ratio DM	0.29	0.0001		0.01	0.22
C:F ratio DM	0.4	0.00006		0.09	0.10
C:S ratio DM	0.67	0.0002		0.08	0.11
	Quadratic: $Y_i = \beta_0 + \beta_1 X_i + \beta_2 X_i^2 + \varepsilon_i$				
	β_0	β_1	β_2		
C/plant	1.19	−0.002	0.000005	0.09	0.16
FHB	112.7	0.007	0.00006	0.006	0.31
CHB	30.87	−0.008	0.00003	0.07	0.18
GHB	22.57	−0.0008	0.00002	0.94	0.05
SHB	81.86	0.015	−0.0001	0.003	0.35
G:F ratio HB	0.2	−0.00005	0.0000004	0.0003	0.46
C:S ratio HB	0.38	−0.0002	0.000001	0.001	0.39
C:F ratio HB	0.28	−0.0001	0.0000005	0.001	0.40
CDM	12.39	0.001	−0.000002	0.001	0.39
GDM	9.05	0.004	−0.000006	0.03	0.24
SDM	18.76	0.002	−0.00002	0.01	0.28
G:F ratio DM	0.29	0.00007	0.0000001	0.03	0.23
C:F ratio DM	0.4	−0.00004	0.0000003	0.17	0.12
C:S ratio DM	0.67	0.0009	0.0000004	0.18	0.12

Table 5. *Cont.*

Variable (Y_i)	Trend				*p*-Value	R^2
	Cubic: $Y = \beta_0 + \beta_1 X_i + \beta_2 X_i^2 + \beta_3 X_i^3 + \varepsilon_i$					
	β_0	β_1	β_2	β_3		
C/plant	1.2	−0.004	0.00002	−0.00000003	0.17	0.17
FHB	113.6	−0.121	0.001	−0.000003	0.02	0.31
CHB	31	−0.062	0.0006	−0.000001	0.89	0.02
GHB	22.86	−0.42	0.0004	−0.0000009	0.89	0.03
SHB	82.38	−0.06	0.0006	−0.000002	0.009	0.35
G:F ratio HB	0.2	−0.0002	0.000002	−0.000000003	0.02	0.44
C:S ratio HB	0.38	−0.0005	0.000004	−0.000000006	0.003	0.42
C:F ratio HB	0.28	−0.0003	0.000002	−0.000000004	0.003	0.41
CDM	12.58	−0.025	0.0003	−0.0000006	0.0001	0.60
GDM	9.2	−0.017	0.0002	−0.0000005	0.0001	0.61
SDM	18.9	−0.018	0.0002	−0.0000004	0.03	0.30
G:F ratio DM	0.29	−0.00005	0.000001	−0.000000003	0.0001	0.72
C:F ratio DM	0.4	−0.0003	0.000002	−0.000000005	0.0002	0.64
C:S ratio DM	0.29	−0.00005	0.000001	−0.000000003	0.0002	0.63

HM, humid base; DM, dry matter; C/plant; cob per plant; FHB, forage yield in HB; SHB, stover yield in DM; CHB, cob yield in HB; GHB, grain yield in HB; CDM, cob yield in DM; GDM, grain yield in DM; SDM, stover yield in DM; F; C:F, cobs-to-forage; G:F, grain-to-forage; C:S, cobs-to-stover; *p*-value, probability values; R^2, coefficient of determination.

3.4. Pearson's Correlations

Table 6 shows the individual Pearson's correlations between the evaluated variables. Almost all correlations were significant ($p < 0.01$). All the variables evaluated in HB highly correlated with the DM yields (r > 0.74); similarly, C:F HB, G:F HB, and C:S HB correlated with the C:F, G:F, C:S DM ratios (r > 0.60). However, FHB highly correlated with the CDM and GDM yields (r > 0.57). Neither SHB nor SDM negatively correlated with cobs or grain DM yields (r varied from 0.23 to 0.48).

Table 6. Pearson's correlations between the yield variables evaluated in the humid base (HB) and dry matter (DM).

	CHB	KHB	SHB	K:F HB	C:S HB	C:F HB	CDM	KDM	SDM	K:F DM	C:S DM	C:F DM
FHB	0.74 ***	0.70 ***	0.98 ***	−0.41 ***	−0.41 ***	−0.42 ***	0.62 ***	0.57 ***	0.72 ***	−0.14	−0.17	−0.14
CHB		0.96 ***	0.58 ***	0.24 **	0.29 ***	0.28 **	0.84 ***	0.80 ***	0.40 ***	0.27 **	0.30 **	0.35 **
KHB			0.54 ***	0.35 ***	0.31 **	0.30 **	0.84 ***	0.86 ***	0.33 **	0.41 ***	0.37 ***	0.37 ***
SHB				−0.58 ***	−0.59 ***	−0.61 ***	0.48 ***	0.44 ***	0.74 ***	−0.26 **	−0.30 **	−0.27 **
Ratios:												
K:F HB					0.93 ***	0.93 ***	0.25 **	0.34 **	−0.52 **	0.70 ***	0.69 ***	0.66 ***
C:S HB						0.99 ***	0.26 **	0.27 **	−0.50 ***	0.60 ***	0.67 ***	0.65 ***
C:F HB							0.26 **	0.26 **	−0.50 ***	0.59 ***	0.66 ***	0.64 ***
CDM								0.97 ***	0.29 **	0.51 ***	0.53 ***	0.55 ***
KDM									0.23 *	0.61 ***	0.58 ***	0.58 ***
SDM										−0.61 ***	−0.62 ***	−0.63 ***
Ratios:												
K:F DM											0.96 ***	0.96 ***
C:S DM												0.99 ***

*, **, or *** represent *p*-values < 0.05, <0.01, and <0.0001, respectively; HM, humid base; DM, dry matter; C/plant; cob per plant; FHB, forage (whole plant) yield in HB; SHB, stover (stalks and leaves) yield in DM; CHB, cob yield in HB; GHB, grain yield in HB; CDM, cob yield in DM; GDM, grain yield in DM; SDM, stover (stalks and leaves) yield in DM; F; C:F, cobs-to-forage ratio; G:F, grain-to-forage ratio; C:S, cobs-to-stover ratio.

4. Discussion

World food security depends on reaching crop and livestock-feeding efficiency. Improving the forage yield and quality is an alternative to reduce the costs of livestock feedstuffs' environmental and economic costs [1,2,15–17].

In Mexico, maize has been a crop for 7000 years. The International Maize and Wheat Improvement Center (CIMMYT) is a Mexican government program [28], focused on preserving seeds and obtaining new varieties primarily adapted to drought and warming to increase the grain and forage yields. Genetic improvement and crop management programs try to balance the production with maize nutritional quality, all related to the total and grain yield and composition, the thickness of the stalks, growing capability, the number of leaves, and the chemical composition and digestibility of the plants [29–33].

In the present study, an Asgrow® (Semillas y Agroproductos Monsanto, S.A. de C.V., Mexico) hybrid was used to test different N fertilization doses. AS-757 is widely commercialized in many countries of America primarily for grain production, although it is also widely used for silage elaboration to feed livestock [34]. In the present study, masculine and feminine inflorescences occurred 64.5 and 65.5 d after sowing, corroborating data reported by Sánchez et al. [35] and Peña et al. [31,36] (63.96 to 64.3 d, and 64.3 to 68.3 d), who evaluated the hybrid at the same crop density.

Inflorescence is affected by crop density, but N fertilization can reduce the negative effects of early inflorescences on grain yield [37]; however, in the present work the inflorescences did not vary across N dose. Nonetheless, orthogonal polynomial analysis detected cubic trends, and N-190 was the optimal dose to delay the inflorescence time.

Almost all yields and C:S, G:F, and C:F ratios evaluated were positively affected when were fertilized with 190 to 240 kg N/ha; furthermore, almost all cubic models of those variables had high R^2 coefficients and were significant, showing that excess N negatively affected all yields and plant proportions, and negatively contribute to GHG emissions through N_2O releasing [3].

N availability affects the foliar area index, and therefore the solar light caption [13,23]. Su et al. [11], using 0, 150, 225, and 300 kg/ha of N, found that grain yield decreased from 3 to 21.9% with an N reduction because of the lower radiation-use efficiency; in turn, the leaf area index increases with the optimal N dose, and thus plant height and weight also improve with the grain yields [13,38].

Optimal N doses from 120 to 360 kg/ha had previously been reported [8,13,19]. In the present study, the individual N application underneath soil might reduce the N optimal dose [24]. However, other factors must be considered to determine the optimal N-dose, such as the variability in soil, topography, hydrology [21], soil humidity [38–40], irrigation [23,24,41], and maize genotype [42].

The C:S, G:F, and C:F ratios are affected by N availability [38], and these ratios' changes might affect the starch, CP, NDF, and digestibility of the whole plant [36,43].

In maize forage, the starch:NDF ratio also affects the DMI, milk production (R^2 = 0.60) [9], and fat milk quality [44]; in addition, the NDF and the starch content of ruminant diets depend on the forage-to-grain ratio, which affect the long-chain unsaturated fatty acid profile at the rumen level, and thereby the milk and meat yields and quality [10,18,45].

Correlation analysis of the present work did suggest that optimal N fertilization can improve both grain and stover yields to assume the double purpose of increasing the grain and stover yields to feed humans and ruminants, or on the other hand, to improve the nutritional quality of forage. According to Khan et al. [12], the correct N fertilization level increased the number of seeds per cob and the plant height, improving the grain and stover yields [8,13,38]. Besides this, an inverse relation between NDF and CP is not only due to the C:S, G:F, and C:F ratios [46,47]. Ming et al. [8] analyzed the composition of the maize stalks, finding that adding N of 225 kg/ha improved the CP contents by 12–44%, and reduced the NDF and acid detergent fiber (ADF) by 5.44–10.1% and 12.04–22.03% (depending the high of the stalks and the N dose).

5. Conclusions

Tendency models allowed to obtain the inflection points among the N fertilization doses and maximum cob and grain yields. The cubic and quadratic models of CDM, GDM, and the G:F, C:F, and C:S DM had the best R^2 values (0.60–0.72; $p < 0.0002$). Although any forage or stover tendency model showed a high R^2, no negative Pearson's correlation was found between SHB and SDM, and CDM and GDM yields (r = 0.23–0.48), suggesting that optimal N fertilization can improve both grain and stover yields. N-190 was the optimal N dose to reach the maximum cob and grain yields, and the best G:F HB, C:S HB, C:F

DM, G:F DM, and C:S DM ratios. Tendency modeling might be useful to avoid overdose fertilization, having the double purpose of increasing the grain and stover yields to feed humans and ruminants, or on the other hand, to improve the nutritional quality of forage.

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