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Evaluation of Silage Corn Yield Gap: An Approach for Sustainable Production in the Semi-Arid Region of USA

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Abstract: Water and nitrogen (N) play an important role in closing the yield gap of crops by reducing associated stresses and yield variability. Field research data coupled to the CSM-CERES-Maize model of Decision Support System Agrotechnology Transfer were used to advance our understanding of the effect of water and N on silage corn growth and yield. The objectives of the study were to determine: (i) the best combination of irrigation water and N for optimum biomass yield, and (ii) the yield gap of silage corn grown at different locations in Wyoming, USA. Field experiments were conducted under sub-surface drip irrigation using a randomized complete block design in a split-plot arrangement with four replications. The main plot was irrigation and consisted of 100% crop evapotranspiration (100ETc), 80% (80ETc), and 60% (60ETc), and the sub-plot was N rates, including 0, 90, 180, 270, and 360 kg N ha^{-1} as urea-ammonium-nitrate. The simulated results indicated full irrigation and at least 150 kg N ha^{-1} as the best combination for silage corn production in Wyoming. Our observed and simulated results show the potential to increase the biomass and reduce the yield gap of silage corn in the region if irrigation water and N are properly managed.

Keywords: irrigation; nitrogen; corn; silage

1. Introduction

Water and nitrogen (N) are essential components for plant growth and development. With increasing water scarcity and the environmental risks associated with nutrient leaching, the need to increase agricultural water use efficiency (WUE) and the efficient use of N is receiving significant attention. Irrigation water and fertilizer N use are likely to face future limitations, which warrants further study aiming at maximizing crop production for achieving maximum net return [1].

Water and N play an important role in closing the yield gap by reducing associated stresses and yield variability [2]. Irrigation management requires a thorough understanding of the crop water needs during the growing season as related to developmental stages as well as management strategies for high yield [3,4]. Irrigation is not only important as a way of supplementing seasonal water needs, but also to ensure that crops get suitable water during critical periods of growth to optimize their yield potential while enhancing WUE. Increasing WUE in agricultural production systems is important in arid and semi-arid regions due to limited supply and growing demand for fresh water [5]. This is especially important in water-scarce regions like Wyoming where crop production is not possible without the practice of irrigation. In turn, such practice is optimized with proper irrigation scheduling in order to maximize economic return [6]. Aside from irrigation water, fertilizer N is a critical input for optimum crop production [7]. Nitrogen promotes rapid growth of corn plants, increases leaf size and quality, and promotes fruit and seed development [8].

In the last decades, a large number of studies have provided the framework to assist farmers in making more informed water and N management decisions [9]. These decisions are influenced by many factors including climatic conditions, soil type, and management practices such as planting date, fertilization timing and water application, genotype, previous crop, N carry-over, and seeding rate. The complex interaction of those factors, along with associated costs, limit agronomic field research at specific points in time and space [10]. Dynamic crop simulation models, which have been shown to be valuable tools to assist field-based research, can be used to significantly shorten the timing of field research and to help advance our understanding of the long-term effect of cropping practices in crop growth and yield and the environment [11]. For instance, Staggenborg and Vanderlip [12] have used crop simulation models in dry-land crop production systems to support field-based research to broaden recommendations to producers. Similarly, Kaur et al. [13] used a modeling approach to test the long-term effects of different tillage practices on growth and WUE of dryland winter wheat grown in western U.S.

A crop model is a quantitative approach for predicting growth, development, and yield of crops under a given set of genetic and environmental variables [14]. A crop simulation model coupled to a decision support system can also be used to obtain information on water use, N uptake, and soil moisture [10]. The Cropping System Model (CSM)-CERES-Maize of the Decision Support System for Agrotechnology Transfer (DSSAT) [10,15] is a model known worldwide. Decision Support System for Agrotechnology Transfer models simulate growth, development, water use, and yield of crops growing under specific conditions as a function of weather, soil water, soil N and carbon, and management of the cropping system [10]. DSSAT contains models for over 42 (version 4.7) crops as well as supporting tools to facilitate the use of the models. Such tools include database management programs for soil, weather, crop management and experimental data, utilities, and application programs (https://dssat.net/) [16,17].

The soil water balance module of DSSAT computes the daily changes in soil water content by soil layer due to infiltration of rainfall and irrigation, vertical drainage, soil evaporation, and root water uptake [18]. Irrigation can be applied at specific growth stages (version 4.7), on specific dates with specified water amounts, or can be triggered when the soil water content drops below a specific fraction of the water-holding capacity in the specified irrigation management depth [10]. With respect to N dynamics, DSSAT simulates its mineralization, denitrification, volatilization, transport, and uptake by plants [19].

The goal of this study was to simulate the response of corn for silage production to irrigation water and fertilizer N at different locations in the semi-arid USA. The specific objectives were to determine: (i) the best combination of irrigation water and fertilizer N for optimum biomass yield, and (ii) the yield gap of silage corn grown at different locations in Wyoming, USA.

2. Materials and Methods

2.1. Field Experiments

Field experiments were conducted at the University of Wyoming Research and Extension Center located in Powell, Wyoming (44°45′32″ latitude N and 108°45′30″ longitude W, and a 1333 masl) during the 2014 and 2015 growing seasons. The daily weather data for 2014 and 2015 are presented in Figure 1. The study area is characterized by a semi-arid climate with an average annual temperature of 6.7 °C, an average annual rainfall of 157 mm, and a growing season of 125 days (www.wrds.uwyo.edu). The soil is characterized as clay loam soil with a pH of 7.9, organic matter of 1.67%, and nitrate-N and P in the top 30 cm soil of 13 mg kg^{-1} and 14 mg kg^{-1}, respectively (www.nrcs.usda.gov).

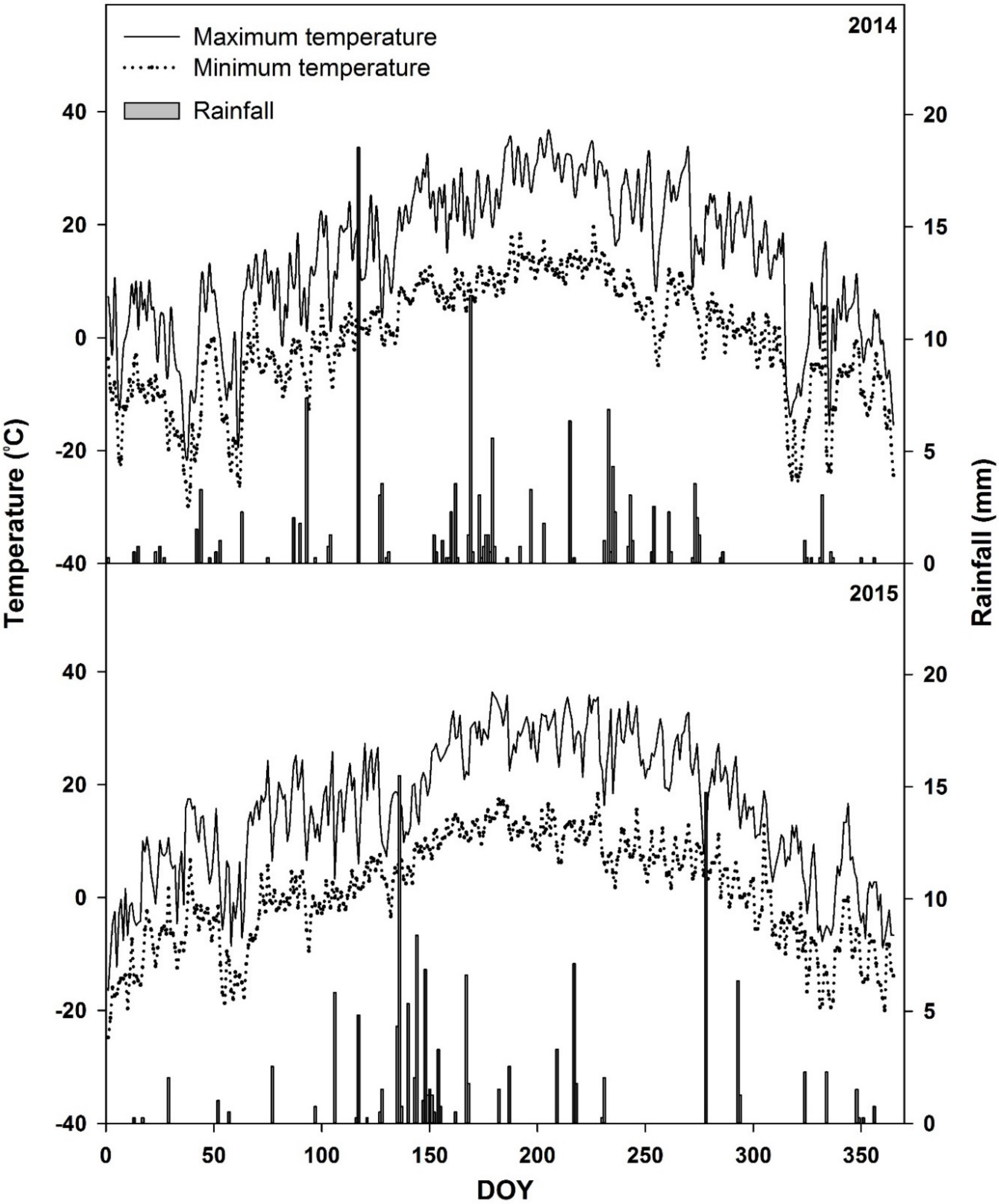

Figure 1. Weather conditions during 2014 and 2015 in Powell, Wyoming. DOY = Day of the year.

The hybrid Pioneer "P8107HR" was planted on 22 May 2014 and 2015 on a subsurface drip irrigated (SDI) field at 56 cm row spacing and a population of 90,000 plants ha^{-1}. The experiment was laid out as a randomized complete block in a split-plot arrangement with four replications. The main plots were irrigation strategies and the subplot N rates. The irrigation treatments included 100ETc, 80ETc, and 60ETc, while the N treatments included 0, 90, 180, 270, and 360 kg N ha^{-1}. The N fertilizer urea-ammonium-nitrate aqueous solution was side-dressed four times on 17 June, 2 July, 15 July, and 22 July 2014, and on 10 June, 25 June, 6 July, and 13 July 2015.

The irrigation scheduling was based on the ETc obtained as a product of the reference evapotranspiration (ET_0) and the dual crop coefficient (K_c) [20,21]. The daily ET_0 was calculated using the FAO Penman–Monteith equation as modified by the American Society of Civil Engineers (ASCE) [22]. Irrigation was triggered when the soil moisture dropped below 50% of the available water in the top 30 cm of soil.

The data collected in the field experiments included leaf area index (LAI), aboveground biomass for growth analysis, and aboveground biomass yield. Plant measurements were obtained during the two years throughout the growing season at five growth stages (V4, V8, V12, VT, and R4 for harvest; V stages were recorded when the collar of a given leaf was visible, VT refers to tasselling, and R4 refers to the reproductive dough stage). Plants in 1-m row lengths of the two inner rows were collected from each plot at each sampling date. The plants were split into leaves, stems, and ears. The leaves were used to obtain the leaf area with an LI-3100C Area Meter (LI-COR Inc., Lincoln, NE, USA). Samples were then oven-dried at 60 °C for a period of 48–72 h before being weighed for aboveground biomass. The occurrence of phenological stages was recorded three times a week on plants in 1-m-row lengths based on the scale of Ritchie et al. [23]. The onset of a given phenological stage was recorded when 50% of the plants were at the stage of interest.

2.2. Modeling Component

Required model inputs included daily weather data, soil profile characteristics, plant-specific information, and management practices (e.g., tillage type, planting date, plant population, fertilization strategy, and irrigation amounts and timing), and grain yield (for model calibration purposes). The daily solar radiation data were obtained from the Climatology Resource for Agroclimatology of NASA (power.larc.nasa.gov). WeatherMan [24], a DSSAT tool to facilitate the preparation of weather information, was used to prepare the weather data in DSSAT format. The soil profile information was obtained from the Soil Characterization Database of the National Resources Conservation Service of the USDA [25]. SBuilt, a DSSAT tool to facilitate the preparation of soil information and estimate missing data, was used to prepare the soil files in a DSSAT format (Table 1).

For model calibration and validation, data collected in 2014 and 2015 were used (Tables 2 and 3). The cultivar coefficients of the CSM-CERES-Maize model (Table 2) were calibrated with data from 2014 using the Genotype Coefficient Calculator (GenCalc; [26]) tool of DSSAT. GenCalc iteratively estimates the genotype coefficients and compares the model outputs with measured data. The coefficients that minimize the sum of the squared error are selected [26] to create the new cultivar (Table 2), which is then used for applications of the model. In order to get the best match between simulated and observed data [27], the model was calibrated with observed data obtained under non-stressed conditions of our field research. Because CSM-CERES-Maize was developed for corn for grain [10], a parallel study using the same genotype and management practices [28] was conducted to obtain grain yield data. Then, the model was run to physiological maturity, but the aboveground biomass for silage corn was extracted from the daily outputs at R4 (dough) growth stage using the cumulative growing degree-days obtained from the field experiment to match the simulated R4. After calibration, the model was validated using the observed field data from the 2015 growing season (Table 3).

Table 1. Soil properties used in the model for Powell (Park County).

Depth (cm)	Master Horizon	Lower Limit (cm^3 cm^{-3})	Upper Limit, Drained (cm^3 cm^{-3})	Upper Limit, Saturated (cm^3 cm^{-3})	Sat. Hydraulic Conductivity (cm h^{-1})	Bulk Density (g cm^{-3})	Organic Carbon (%)	Clay (%)	Silt (%)	Coarse Fraction (%)	pH in Water	CEC [§] (cmol kg^{-1})
3	A1	0.208	0.390	0.410	1.32	0.82	8.34	15.4	37.0	37.0	4.9	28.4
13	A2	0.153	0.303	0.353	1.32	0.98	5.37	14.9	35.1	38.0	4.8	23.6
25	A3	0.078	0.171	0.293	1.32	1.23	1.84	11.3	36.9	41.0	5.0	16.0
46	Bs1	0.051	0.123	0.258	2.59	1.35	0.61	9.60	38.1	44.0	4.9	14.5
66	Bs2	0.050	0.114	0.241	2.59	1.42	0.38	10.9	34.2	45.0	4.8	14.9
107	Bt	0.051	0.116	0.240	1.32	1.43	0.22	12.2	36.4	45.0	5.2	16.3
178	2C	0.041	0.092	0.323	6.11	1.55	0.05	4.50	13.2	18.0	6.8	13.2

[§] CEC = Cations exchange capacity.

Table 2. The calibrated corn cultivar coefficients for the cultivar PIO8107HR14.

Code	Definition	Default	Calibrated
P1	Thermal time from seedling emergence to the end of juvenile period (>8 °C degree days)	200	153.6
P2	Extent to which development is delayed for each hour when the photoperiod is greater than 12.5 h	0.7	0.51
P5	Thermal time from silking to physiological maturity (degree days)	800	950
G2	Maximum possible number of kernels per plant	715	810
G3	Kernel optimum filling rate during the linear grain filling stage (mg d^{-1})	8.5	8.6
PHINT	Phylochron interval between successive leaf tip appearances (degree days)	38.9	46.17

Table 3. Measured and simulated data for the model calibration (2014) and validation (2015).

Year	Treatment	LAI (m^2 m^{-2})					Aboveground biomass (kg DM ha^{-1})				
		Observed	Simulated	R^2	RMSE	d-Stat	Observed	Simulated	R^2	RMSE	d-Stat
2014	100ETc 0 N	1.99	2.26	0.92	0.58	0.94	6433	6404	0.74	3197	0.92
	100ETc 90 N	2.05	2.28	0.93	0.60	0.93	6118	6384	0.84	2374	0.96
	100ETc 180 N	2.31	2.27	0.92	0.66	0.93	7092	6395	0.90	2332	0.97
	100ETc 270 N	2.40	2.82	0.99	0.45	0.98	7503	7170	0.91	2199	0.98
	100ETc 360 N	2.19	2.3	0.93	0.66	0.93	7350	6397	0.92	2534	0.96
2015	100ETc 0 N	1.63	1.70	0.92	0.28	0.97	7246	5508	0.98	2117	0.96
	100ETc 90 N	1.91	2.59	0.67	0.99	0.85	8610	6788	0.95	2355	0.97
	100ETc 180 N	1.85	2.00	0.59	0.72	0.88	8959	6788	0.95	2599	0.96
	100ETc 270 N	1.99	2.60	0.70	0.92	0.86	8050	5354	0.98	3172	0.94
	100ETc 360 N	1.88	2.00	0.69	0.62	0.91	8142	5354	0.98	3239	0.94

d = Index of agreement; RMSE = root mean square error; LAI = leaf area index.

The calibrated CSM-CERES-Maize model was used to simulate the response of corn to water and N for conditions at three locations (i.e., Powell, Sheridan, and Lingle) in Wyoming, USA. For each location, the model was set to trigger irrigation when the soil available water at a management depth of 30 cm dropped below 50%. For each location, the seasonal analysis of DSSAT was set to run for a period of 31 years (1985–2015) to simulate growth, development, and N uptake of maize, and to determine the WUE of the crop. The long-term weather data was obtained from the NOAA-NCDC [29], the soil profile information for each location was obtained from the USDA-NRCS [25], and the management practices were kept the same as in the experimental field at all locations. The automated irrigation scenario (irrigation water applied when needed (IN)) combined with different rates of N from 0 kg N ha^{-1} to 360 kg N ha^{-1} were included in the model. The model was also set to simulate the potential yield of maize. To do so, at each location the CSM-CERES-Maize model simulated the growth and development of maize assuming no water and no N limitations.

The yield gap, defined as the difference between potential yield and actual (treatment) crop yield [30,31], was used to quantify and determine potential improvements of maize for silage yield across Wyoming. The yield gap was calculated for each N treatment of the 31-year outputs from each location, as compared to the model outputs for potential yield as in Equation (1).

$$\text{Yield gap (\%)} = \frac{\text{Potential aboveground biomass} - \text{Treatment aboveground biomass}}{\text{Treatment aboveground biomass}} \times 100. \quad (1)$$

2.3. Statistical Analysis

The CSM-CERES-Maize model performance was evaluated by comparing the simulated and measured results using three statistics, including coefficient of determination (R^2), the Willmott [32] index of agreement (d; Equation (2)), and the root mean square error (RMSE) (Equation (3); [33]).

$$d = 1 - \frac{\sum_{i=1}^{n}(m_i - s_i)^2}{\sum_{i=1}^{n}\left(|\dot{s}_i| - |\dot{m}_i|\right)^2} \quad (2)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n}} \quad (3)$$

where n is the number of measured dataset, s_i is simulated data, m_i is ith measured data, $\overline{m}$ is the mean of the measured data. $\dot{s}_i = s_i - \overline{m}$; $\dot{m}_i = m_i - \overline{m}$. The closer the d-index of agreement to 1, the better the simulated results fit the observed data [32]. Conversely, the lower the RMSE, the better the model simulates the observed data [33].

The model outputs, including LAI, aboveground biomass, N uptake, and WUE, were analyzed using the PROC GLM procedure of the SAS statistical package [34] (SAS v. 9.4; SAS Institute, Inc., Cary, NC, USA). A post-hoc Least Significant Difference (LSD) mean separations was performed using the PROC MEANS of SAS. Data were checked for homogeneity of variances using the Bartlett test [35], and for normality of residuals using the Shapiro–Wilk test [36].

3. Results and Discussion

3.1. Observed Data

The LAI and aboveground biomass data collected during 2014 and 2015 growing seasons were used to calibrate and validate the CSM-CERES-Maize model (Table 3). For both the 2014 and 2015 results, high LAI values were obtained with the combination of 100ETc and 270 kg N ha^{-1} (Table 3). Similarly, high aboveground biomass was obtained with the combination of 100ETc and 270 kg N ha^{-1}, and 100ETc and 180 kg N ha^{-1} in 2014 and 2015, respectively (Table 3). The LAI decreased with a decrease in fertilizer N, which is reported to reduce leaf expansion due to reduction on leaf length and leaf width [37,38]. Likewise, LAI decreased with water stress, which is reported to be the consequence of reduced photosynthetic assimilates as a result of accelerated stomatal closure [39]. The increase of the aboveground biomass with increased N rates was due to the increase of leaf expansion leading to increase of leaf absorption of photosynthetically active radiation [40], and accumulation of assimilates which increased the biomass of silage corn [41,42]. Similarly, aboveground biomass increased with irrigation water as a result of enhanced gas exchange (CO_2, H_2O) and sufficient supply of assimilates to get the plants to their final size and weight [43].

3.2. Model Calibration

The derived crop coefficients for the cultivar PIO8101HR14 (Table 2) allowed the model to satisfactorily simulate the anthesis date, which occurred 79 days after planting (DAP) compared to 80 DAP observed. The physiological maturity date was predicted to occur at 140 DAP compared to 143 DAP observed. The model also satisfactory simulated the LAI; the simulated average LAI in 2014 was 2.27 compared to 2.31 observed for the 100ETc 180 N treatment (R^2 = 0.92; *d*-index = 0.93; RMSE = 0.66 m^2 m^{-2}) (Table 3). For the aboveground biomass, the model slightly underestimated the observed values (6395 kg DM ha^{-1} simulated versus 7092 kg DM ha^{-1} observed for 100ETc 180 N treatment) with an R^2 equal to 0.90, *d*-index of 0.97, and the RMSE equal to 2332 kg ha^{-1} (Table 3).

The model validation using 2015 data showed that the simulated and the observed values for LAI and aboveground biomass were acceptable (R^2 = 0.59; *d*-index = 0.88; RMSE = 0.72 m^2 m^{-2} for LAI, and R^2 = 0.95; *d*-index = 0.96; RMSE = 2599 kg ha^{-1} for aboveground biomass under 100ETc 180 N treatment; Table 3), indicating the suitability of the CSM-CRES-MAIZE model for broader use in the region.

3.3. Long-Term Simulation of Silage Maize Growth and Development

For the irrigation water applied, the averaged 31-year period of simulated value were comparable to the amount of water applied (Table 4). The seasonal irrigation water applied was 257 mm compared to 249, 262, and 280 mm for Powell, Sheridan, and Lingle, respectively (Table 4). This indicates that the water applied under subsurface drip irrigation was close enough to what the maize needed for adequate growth and development.

Table 4. Irrigation water applied (mm) during the growing season compared to simulated data for the three locations.

DOY	Measured	Simulated			
		Powell	Sheridan	Lingle	Pooled Average
170	6	0	3	0	1
173	7	2	1	2	2
175	4	2	1	4	2
180	10	10	6	18	11
186	17	16	14	18	16
191	18	14	16	22	17
199	25	31	30	31	31
203	10	14	19	17	17
206	28	13	12	19	15
213	28	30	32	27	30
220	23	27	26	29	27
227	28	28	28	26	27
240	25	29	38	35	34
250	28	32	36	34	34
Total	257	249	262	280	263

DOY = Day of the year.

The 31-year outputs of the model were averaged to determine the LAI of maize for different N rates under the "IN" scenario (Figure 2). The LAI increased with increased N rate and showed a maximum at 180 kg N ha^{-1} for Powell and Sheridan conditions, and 120 kg N ha^{-1} for Lingle. The LAI values were stable with no significant difference above these rates. The LAI increase with increased N are reported to be due to leaf expansion and high photosynthetic rate under no stress conditions [6,44]. The average LAI across the three locations showed that 150 kg N ha^{-1} maximized LAI of corn for silage, indicating its stability across the state.

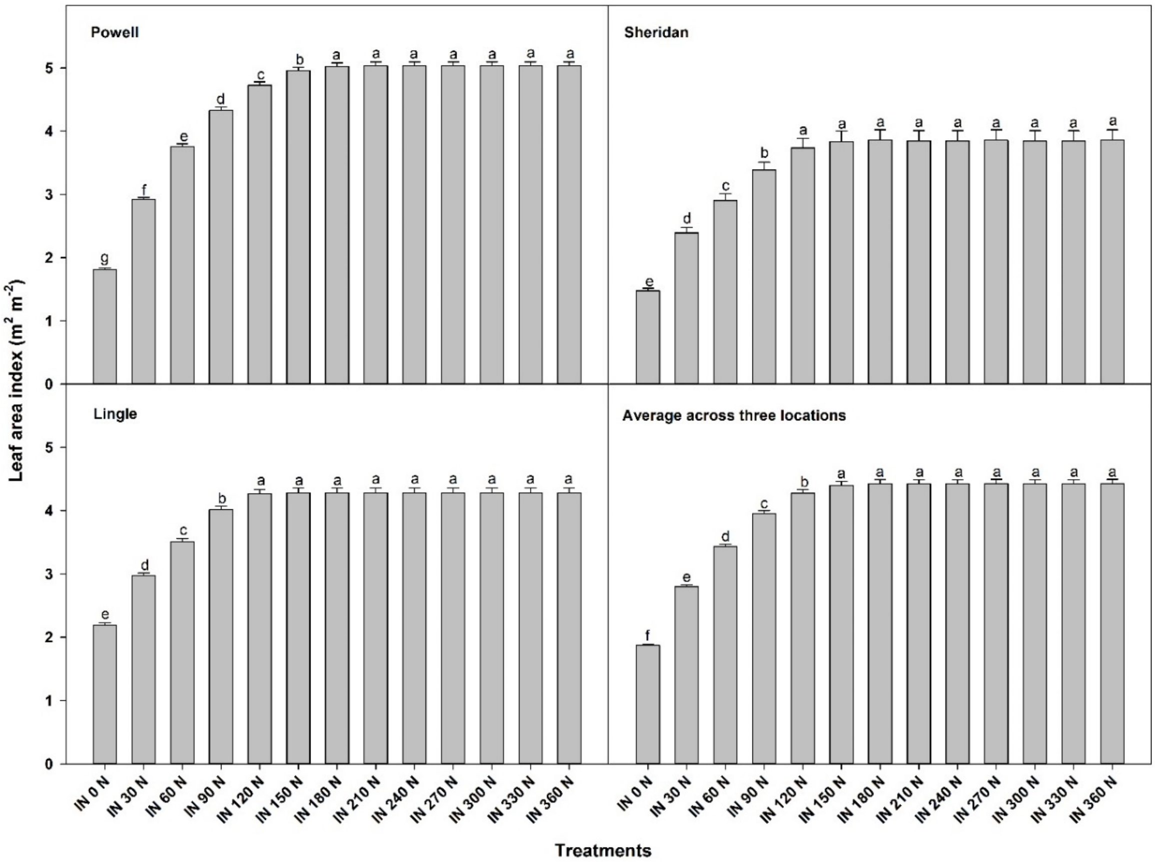

Figure 2. Seasonal analysis for leaf area index at the three locations that were evaluated and the average across the three locations using 31 years of data. IN = Irrigation water applied when needed. Within location, means with different letters are significantly different based on the Least Significant Difference (LSD) (0.05). The error bars indicate the standard error.

The aboveground biomass showed high values when at least 180, 150, and 180 kg N ha^{-1} applied for Powell, Sheridan, and Lingle, respectively (Figure 3). Geographically, high aboveground biomass values followed a trend of Lingle > Sheridan > Powell, which reflected the better soil and weather conditions for maize growth in Lingle compared to other locations. The aboveground biomass across the locations indicated that at least 180 kg N ha^{-1} is needed for optimum silage corn biomass in Wyoming.

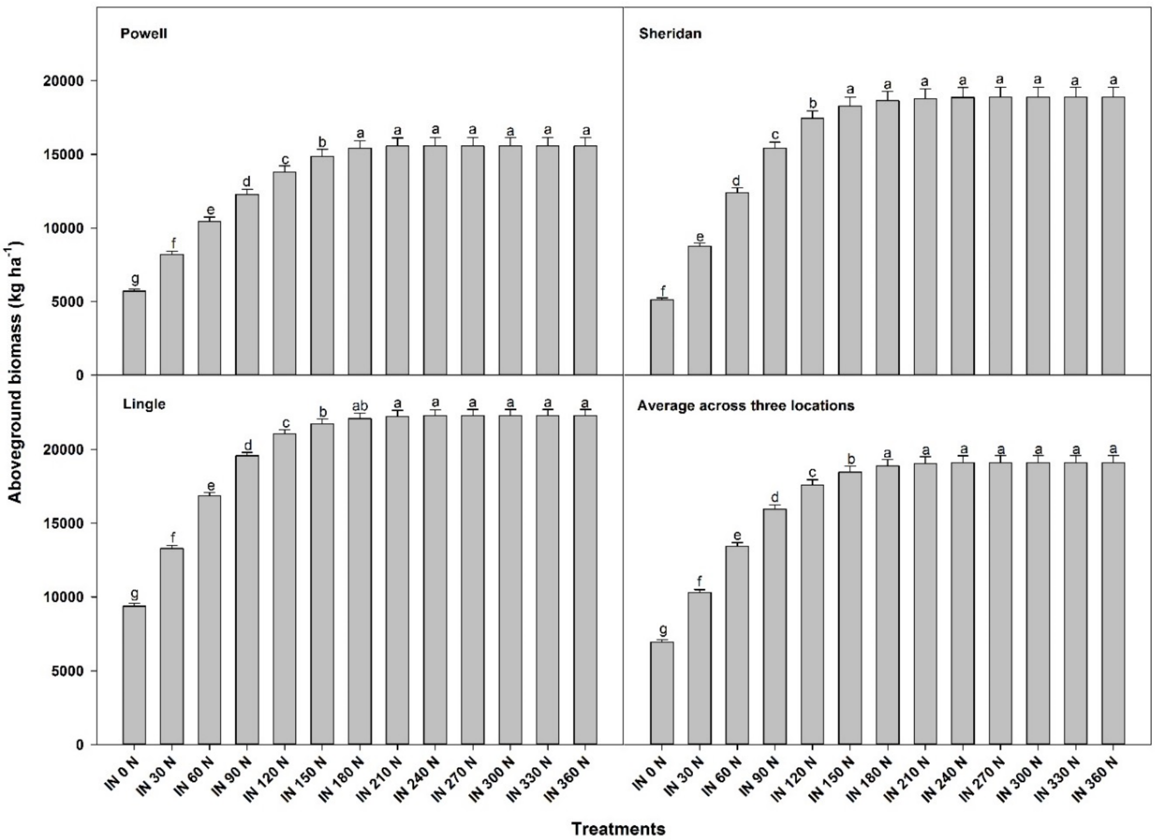

Figure 3. Seasonal analysis for aboveground biomass at the three locations that were evaluated and the average across the three locations using 31 years of data. IN = Irrigation water applied when needed. Within location, means with different letters are significantly different based on the Least Significant Difference (LSD) (0.05). The error bars indicate the standard error.

The seasonal N uptake of maize showed high values under at least 210 kg N ha^{-1} for Powell, and at least 240 kg N ha^{-1} for both Sheridan and Lingle (Figure 4). The N used by corn increased with increased N, and followed a trend of Lingle > Sheridan > Powell. The average across the three locations showed that at least 240 kg N ha^{-1} is needed for maximum N uptake. As for WUE, the simulated values followed a similar pattern as the aboveground biomass with high values starting at 180 kg N ha^{-1} for Powell and Lingle, and 150 kg N ha^{-1} for Sheridan (Figure 5). The average across the three locations indicated that at least 180 kg N ha^{-1} is needed to improve the WUE.

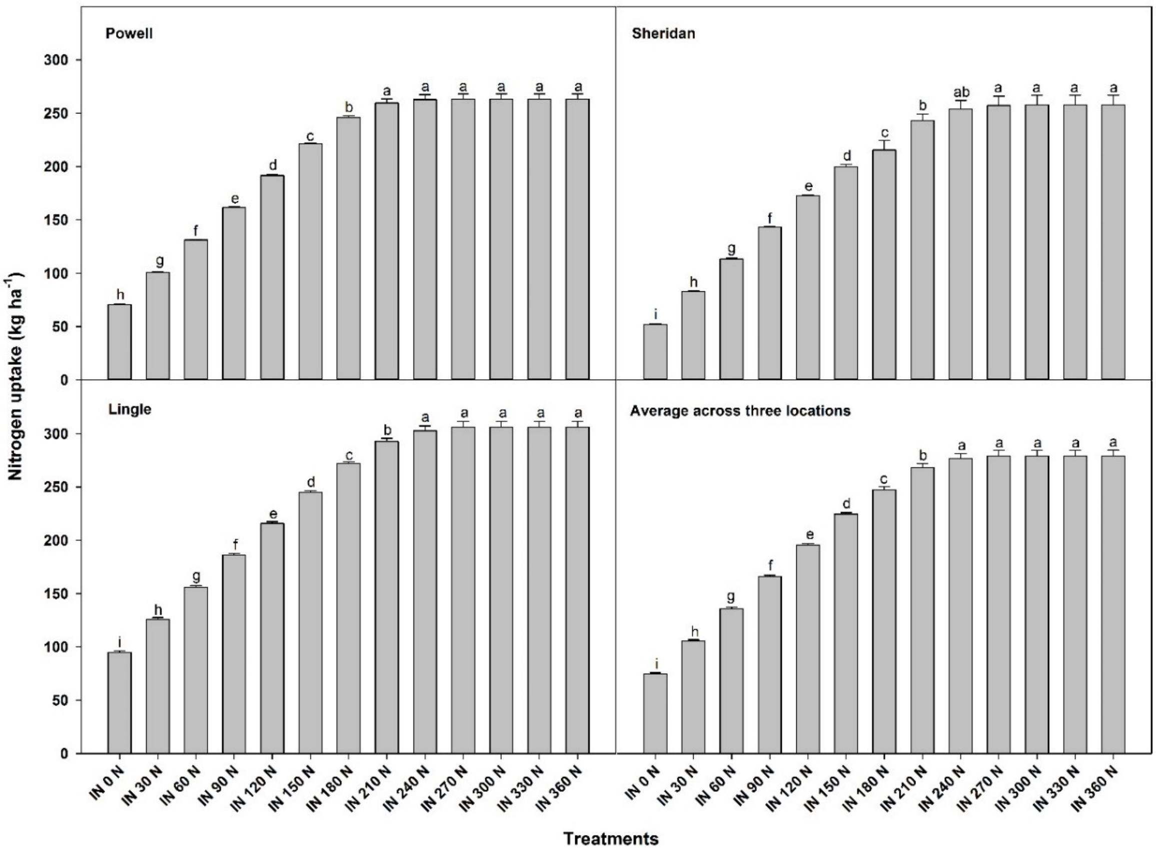

Figure 4. Seasonal analysis for N uptake at the three locations that were evaluated and the average across the three locations using 31 years of data. IN = Irrigation water applied when needed. Within location, means with different letters are significantly different based on the Least Significant Difference (LSD) (0.05). The error bars indicate the standard error.

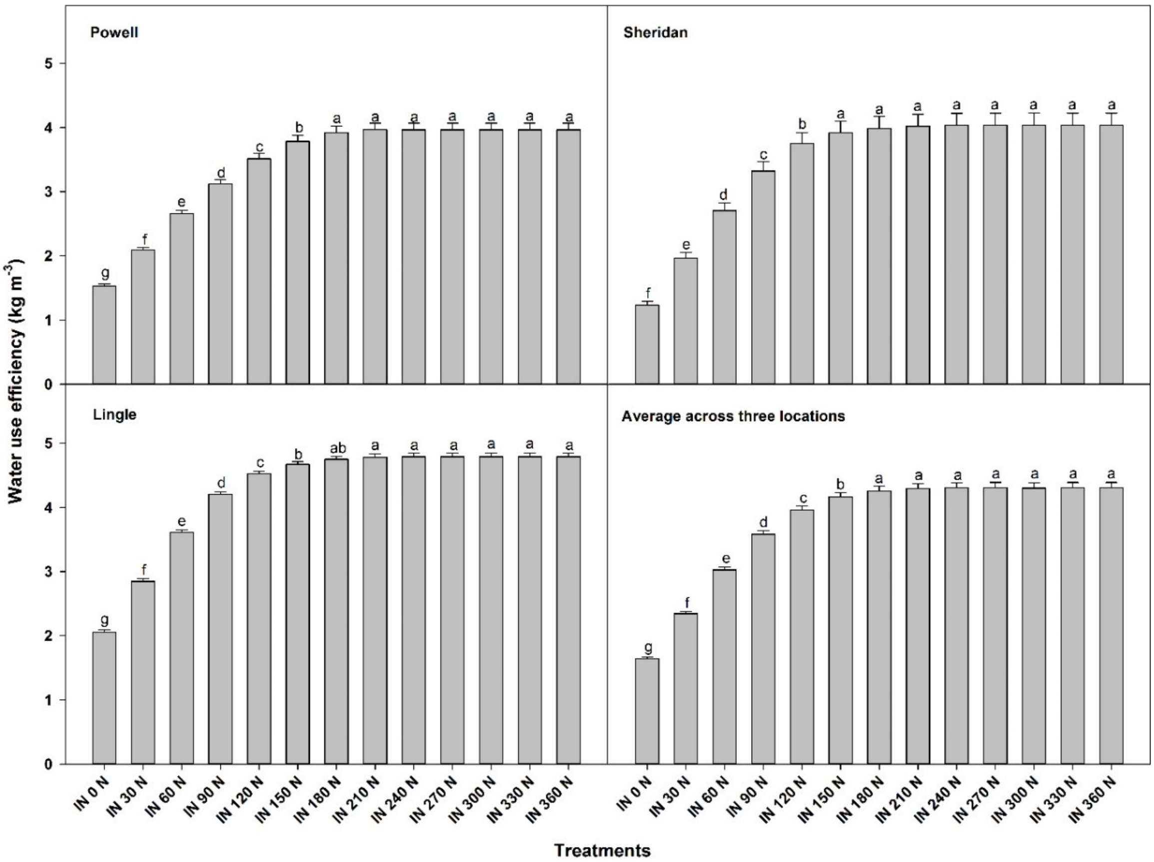

Figure 5. Seasonal analysis for water use efficiency at the three locations that were evaluated and the average across the three locations using 31 years of data. IN = Irrigation water applied when needed. Within location, means with different letters are significantly different based on the Least Significant Difference (LSD) (0.05). The error bars indicate the standard error.

In summary, the long-term simulated results indicated that water and N fertilizer rate affected LAI, aboveground biomass, N uptake, and WUE of corn grown in different locations of Wyoming. For conditions in northern Florida, He et al. [45] used the CSM-CERES-Maize model to identify the best N rate on sandy soils using 33 years of data, and reported that the optimal rate of N fertilizer ranged between 196 kg N ha^{-1} to 224 kg N ha^{-1}. Our simulated results showed high LAI, aboveground biomass, N uptake, and WUE for N rates ranging between 150 kg N ha^{-1} to 180 kg N ha^{-1}.

3.4. Potential Yield, Yield Gap, and Opportunities for Increasing Silage Corn Yield

The yield gap analysis enabled the advancement of our understanding of the impact of water and fertilizer N in silage corn production in semi-arid Wyoming. In comparison with the potential yield, our simulated results indicate that the yield gap of silage corn could be reduced to less than 10% if 120 kg N ha^{-1} is applied with a proper irrigation amount (Table 5). The model results showed that the yield gap was reduced to 5%, 4%, and 3% under the IN 150 kg N ha^{-1} scenario for Powell, Sheridan, and Lingle, respectively (Table 5). The pooled average across the three locations indicates a potential to increase silage corn biomass and greatly reduce the yield gap to less than 5% if no less than 150 kg N ha^{-1} is applied (Table 5). The yield gap greatly reduced with the increasing rates of fertilizer N, suggesting the potential to increase the silage corn biomass if N rates are optimized.

Table 5. Yield gap (%) of the treatments used for corn grown for silage in Wyoming.

Treatment	Powell	Sheridan	Lingle	Pooled Average
IN 0 N	173	271	139	194
IN 30 N	90	117	68	92
IN 60 N	49	53	33	45
IN 90 N	27	23	14	22
IN 120 N	13	9	6	10
IN 150 N	5	4	3	4
IN 180 N	1	2	1	2
IN 210 N	0	1	1	1
IN 240 N	0	1	0	1
IN 270 N	0	1	0	0
IN 300 N	0	1	0	0
IN 330 N	0	1	0	0
IN 360 N	0	1	0	0

IN = Irrigation water applied when needed.

4. Conclusions

The present study used a combination of field research and modeling to assess the response of corn for silage production to water and N at different locations in the semi-arid climate of Wyoming. The model provided acceptable outputs in which the simulated results were in agreement with the observed values. The simulated multi-year results indicated that water and N affected LAI, aboveground biomass, N uptake, and WUE of corn for silage grown in the semi-arid western region of the USA. At least 150 kg N ha^{-1} was needed to obtain highest LAI, aboveground biomass, N uptake, and WUE. The simulated results demonstrated stability across locations, suggesting the suitability of the model for broader use in the region. Our simulated results also indicated that the region has the potential to increase the aboveground biomass of corn for silage and to reduce the yield gap provided that irrigation water and N fertilization practices are well managed.

Author Contributions: A.N. designed the experiment, collected, and analyzed results, set up and executed the modeling component, and led the writing of the manuscript; M.A.I. administered and supervised the overall project, led and guided the lab and field work, contributed to funding, and reviewed the manuscript; A.O.M. conceptualized the study, helped in designing the study, agronomic management and obtaining funds, and reviewed the manuscript; A.G.G. contributed to the inception of the project and funding management, the design of the experiment, the setup of the modeling component, and reviewed the manuscript.

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