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Research Article

Growth and nitrogen uptake modeling in composite and hybrid corn varieties

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ABSTRACT

Corn is a strategic commodity in Indonesia's agricultural and economic development. The problem of corn production can be overcome with proper usage of nitrogen fertilization. Dynamic modeling can be used as a tool to solve this problem. This study aimed to develop a dynamic model for the growth and nitrogen uptake of composite and hybrid corn varieties. Stages in the model construction: (1) identifying system components, (2) model construction, (3) simulation, and (4) validation. The growth model is a construction of the plant's ecophysiological response to solar radiation and temperature in photosynthesis. A growth model in composite and hybrid corn varieties with simulated dry weight as output has been constructed validly. The model input components, such as light use efficiency, extinction coefficient, specific leaf area, and carbohydrate partition coefficient varied at each development phase for each variance. The actual total dry weight on the Pioneer 27 variety was 6,406 kg ha^{-1} with a simulated total dry weight was 6,228 kg ha^{-1}, and the actual total dry weight on the Bisma variety was 5,127 kg ha^{-1} with a simulated total dry weight was 4,864 kg ha^{-1}. The level of validity of the Pioneer 27 variety growth model reached 83.5% and the Bisma variety reached 80%.

Keywords: Bisma; dry weight; growth model; nitrogen uptake; Pioneer 27; simulation; validation

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INTRODUCTION

Corn (*Zea mays* L.) is an important carbohydrate in the world after rice and wheat; it also has high economic value in Indonesia (Bhato, 2016). Based on data from the Ministry of Agriculture (2021), corn production in 2018, 2019, and 2020 tends to decrease compared to 2017, namely only 22.65 million tons, 22.58 million tons, and 22.92 million tons, respectively as compared to 2017 amounted 28.92 million tons. However, corn productivity in 2023 only reached 5.82 tons ha^{-1} as it still has not reached the potential productivity of good composite variety (e.g., Bisma: 7.5 tons ha^{-1}) and hybrid variety (e.g., Pioneer 27: 11 tons ha^{-1}).

One of the limiting factors in corn production is the fertilization process. The availability of nitrogen (N) in the soil is one of the factors that influences corn yields; and it is affected by crop rotation, tillage, and soil type (Tao et al., 2018). Nitrogen plays an important role in plant metabolic processes as well as vegetative and generative growth of corn through stimulating leaf growth and photosynthetic activity and efficiency (Gheith et al., 2022). The application of N can also increase leaf area index, enzyme activity, chlorophyll levels, and light absorption efficiency (Leghari et al., 2016). Tian et al. (2021) revealed that a high level of chlorophyll correlates with high nitrogen application. The N application increases the interception of PAR (photosynthetically active radiation) value by 33% in corn plants compared to without nitrogen application (Luo et al., 2021), and can increase corn grain yield by 43-65.91% and biomass dry weight by up to 25-42% (Yue et al., 2022). Thus, low N availability in the soil needs improvement through fertilizer application.

Recommendations for corn fertilization must be able to describe maximum nutrient uptake on varied fields so that fertilization becomes efficient and effective. One approach to fertilizer recommendations is to create a model for nutrient uptake. Crop simulation models can be used as decision support systems to assess the risk and economic impacts of management strategies in agriculture (Kephe et al., 2021). This research aimed to develop a model to predict growth and production in relation to N uptake in two corn varieties, composite and hybrid.

MATERIALS AND METHODS

Ekperimental site and design

The development of growth and nitrogen uptake models of open-pollinated and hybrid corn varieties was carried out using literature studies and field experiments. The literature study began from January to June 2022 using literature published from 2015 to 2022. Field experiments were carried out at the Cikabayan Experimental Station, IPB University from June to December 2022. Soil analysis was carried out at the Soil Research Institute, Bogor.

The materials utilized include findings from previous plant modeling research to construct the model, climate data from the Darmaga Climatology Station for model input, and constants, variables, and experimental results for validating the model. Field experiment used the Bisma variety (composite) and the P27 (Pioneer 27) variety (hybrid), urea 46% N, SP36 (36%P_2O_5), and KCl (60%K_2O). The lux meter used was a Li-250A lux meter. Data analysis was performed using the Stella 9.02 application.

System component identification

The corn growth and development were divided into four sub-models, i.e., growth, development, water balance, and nitrogen uptake. The plant growth sub-model was built based on the mass flow of energy that occurs as a result of the photosynthesis process. The plant development sub-model was built based on the concept of thermal units (TU) obtained at each development phase, namely the field emergence phase, vegetative growth phase, flowering phase, and cob filling phase.

The water balance sub-model was built based on water mass flow from interception to transpiration. Water availability to plants was formulated as the ratio between actual transpiration to maximum transpiration. The nitrogen nutrient uptake sub-model was built based on the mass flow of nitrogen nutrients in the soil and its loss through nitrogen uptake by plant roots. Nutrient availability to plants was formulated as the ratio between actual nitrogen levels to maximum nitrogen levels.

Model construction

Initially, a flow diagram was constructed, followed by determining logical mathematical relationships between variables. Here, the processes and system variables were integrated into a model. The process of assembling the variables in the system was carried out using Stella software version 9.02 to form the Model Construction Layer-Stella (MCL-S). The mathematical equation relationships in MCL-S were arranged in Equation Layer–Stella (EL-S).

Field experiments were carried out to obtain constant values or model variables for model development, and to obtain actual data on the dry weight of corn at various times for model verification. Field experiments were carried out by planting corn with a spacing of 80 cm x 20 cm, with a plot area for each experiment of 5 m x 3 m = 15 m^2. Corn was planted one seed per planting hole. Fertilizer was applied at a dose of 350 kg ha^{-1} Urea, 150 kg ha^{-1} SP-36, and 150 kg ha^{-1} KCl (Masruroh et al., 2017; Li et al., 2017; Supandji & Saptorini, 2019).

The variables and parameters measured for developing growth models included weather components, soil components, and plant components. The daily weather was recorded for the amount of solar radiation (Q_s) and daily temperature (T). Data was obtained from the West Java Climatology Station, Bogor. The soil components included soil density, field water capacity (KL), and permanent wilting point (TLP). The plant components were extinction coefficient (k), specific leaf area (SLA), light use efficiency (e), partition coefficient (η), and dry weight of each plant organ. The constant values in the model were obtained from literature, i.e., maintenance respiration coefficient (K_m) and base temperature of corn (T_o).

Agroclimate components included solar radiation, temperature, rain, wind, and humidity. Temperature influenced the sub-model of plant development through heat flow. Solar radiation affects the water balance sub-model and growth sub-model through the flow of radiation energy. The nitrogen uptake influenced the flow of nitrogen nutrients from the soil which was absorbed by the roots and to the growth sub-model by the nitrogen uptake factor. Rain affected the soil water balance sub-model through water flow, which was also influenced by air humidity and wind. The soil water balance sub-model produced water availability factors that influenced the plant growth sub-model and the nitrogen uptake sub-model to determine the nitrogen absorbed by plant roots.

Model simulation

The simulation was carried out using the MCS-L growth model for corn varieties Bisma and Pioneer 27. The model simulated changes in the dry weight of plant organs at different urea levels of 0, 175, 350, 525, and 700 kg ha^{-1}. The simulation included extinction coefficient, light use efficiency, specific leaf area, dry weight partition of every plant organ, and weather and soil components. The simulation results were assessed for their level of validity (logic) to determine the model validity.

Model validation

Model validation was carried out through qualitative methods using graphs. The model was considered valid if 80% of the simulation results fall within the standard deviation interval of the actual results.

RESULTS AND DISCUSSION

System component identification

Plant growth was determined by two processes, namely the products of photosynthesis and the rate of respiration from each plant organ. The energy balance in the plant was manifested as the dry weight of the plant, which was distributed to the roots, stems, leaves, and cobs.

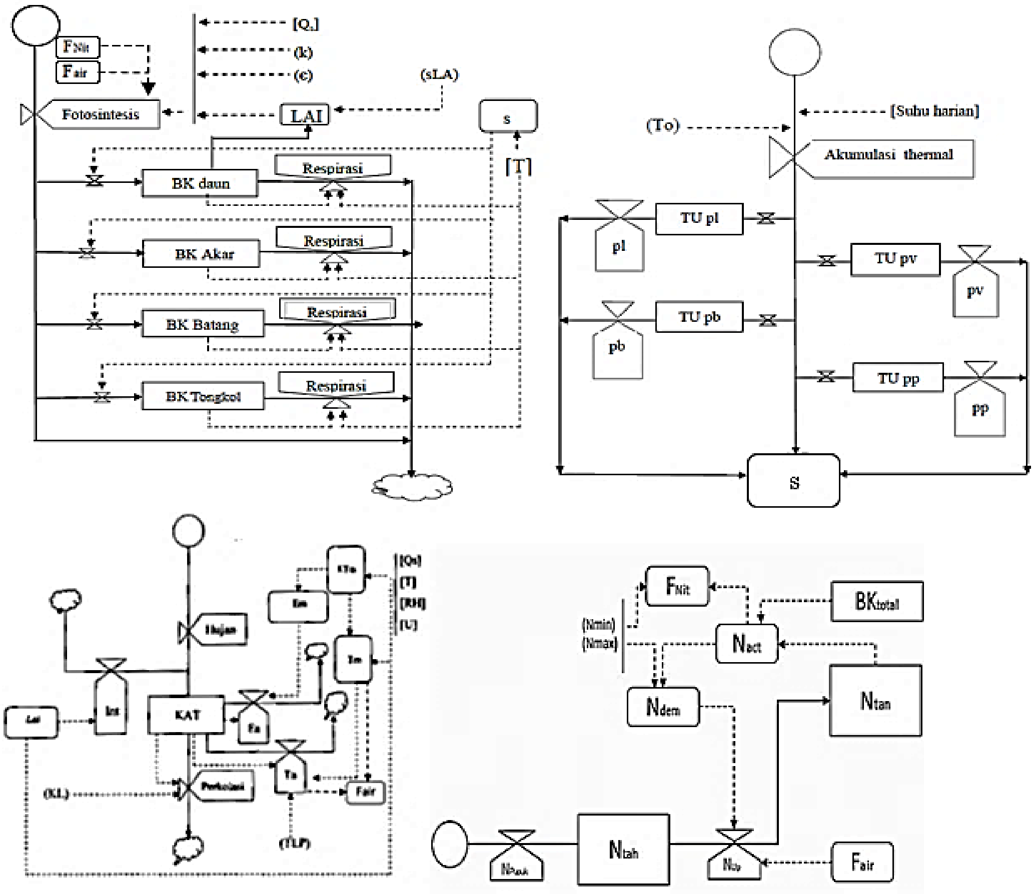
Model construction

Referring to Qadir (2012), the flow diagram of the growth and nitrogen uptake model for corn plants can be described in Figure 1. Photosynthesis products during growth are calculated using the following equation:

$$P_n = \varepsilon \times \left(1 - e^{-(k \times LAI)}\right) \times Q_s \times F_{wat} \times F_{Nit}$$

Net photosynthesis (P_n) for each corn plant variety varies on the leaf area index (LAI), ε value (light use efficiency), extinction coefficient (k), solar radiation (Q_s), water availability factor (F_{wat}), and nitrogen uptake factor (F_{Nit}). Variations in coefficient values for each variety indicate differences in the amount of photosynthesis products produced.

Light use efficiency (ε) describes how efficiently plants use light for growth (Legendre & van Iersel, 2021). The ε value in Bisma and Pioneer 27 corn varieties from the field emergence (Eme), maximum vegetative (MaxVeg), and anthesis (Ant) to harvest (Harv) phases is presented in Table 1.



————— = mass flow
-------- = information flow
O = source
( ) = parameter
⧗ = flow
[ ] = external variable
▬ = condition variable
▬ = auxiliary variable
= sink
T = temperature
Qs = solar radiation
k = light extinction coefficient
ε = light use efficiency
LAI = leaf are index
SLA = specific leaf area
BK = dry weight
s = development phase
To = plant base temperature
TU = thermal units
pl = emergence
pv = vegetative growth
pb = flowering/anthesis
p = harvest
RH = relative humidity
Int = canopy interception
KAT = soil water capacity
KL = field capacity
TLP = permanent welting point
Ea = actual evaporation
Em = maximum evaporation
Etm = maximum evapotranspiration
Tm = maximum transporation
Ta = actual transporation
F_{air} = water availability factor
N_{tah} = soil nitrogen content
N_{pupuk} = nitrogen addition from fertilizer
N_{up} = nitrogen uptake
N_{tan} = plant nitrogen content
N_{min} = minimum plant nitrogen content
N_{max} = maximum plant nitrogen content
N_{dem} = plant nitrogen demand
N_{act} = actual plant nitrogen content
F_{Nit} = nitrogen uptake factor

Figure 1. Forrester diagram model of growth, development, water balance, and nitrogen uptake.

Table 1. Light use efficiency (ε) in four development phases of Bisma and Pioneer 27 corn varieties.

Variety	Light use efficiency (kg/MJ)				
	Plant-Eme	Eme-MaxVeg	MaxVeg-Ant	Ant-Har	Average
Pioneer 27	0.0000a	0.00334b	0.00568b	0.00378b	0.00320b
Bisma	0.0000a	0.00320a	0.00522a	0.00342a	0.00296a

Note: Numbers followed by the same letter in the same column are not significantly different based on the t-test at α = 5%. (Eme=emergence, MaxVeg=maximum vegetative, Ant=anthesis, Har=harvest).

The results show that the Pioneer 27 variety had a higher ε value at each development phase compared to the ε value of the Bisma variety. Gitelson & Gamon (2015) stated that different light use efficiency values are influenced by the amount of radiation arriving at the canopy surface, leaf area index, leaf position or angle, and leaf distribution in the canopy.

The light extinction coefficient (k) is related to the plant's ability to intercept solar radiation (Lacasa et al., 2021). Light extinction coefficients at various development phases are presented in Table 2. The results showed that the Pioneer 27 variety had a lower k value than Bisma in the emergence - field to vegetative phase, but Bisma had a higher k value in the vegetative phase - harvest.

Table 2. Light extinction coefficient (k) in four development phases of Bisma and Pioneer 27 corn varieties.

Variety	Light extinction coefficient				
	Plant-Eme	Eme-MaxVeg	MaxVeg-Ant	Ant-Har	Average
Pioneer 27	0.00a	0.18a	0.43a	0.35a	0.24a
Bisma	0.00a	0.21b	0.40a	0.31b	0.23b

Note: Numbers followed by the same letter in the same column are not significantly different based on the t-test at α = 5%. (Eme=emergence, MaxVeg=maximum vegetative, Ant=anthesis, Har=harvest).

Leaf area index (LAI) is an internal variable that acts as an auxiliary variable in the growth model. LAI value can be used to estimate or calculate plant biomass formation in the growth modeling process (Cahyanti, 2020). In the present experiment, LAI was formulated as a function of leaf area and leaf dry weight at each plant phase which was expressed as specific leaf area (SLA). The results of SLA measurements as a model constant are presented in Table 3.

Table 3. Specific leaf area (SLA) in four development phases of Bisma and Pioneer 27 corn varieties.

Variety	Specific leaf area				
	Plant-Eme	Eme-MaxVeg	MaxVeg-Ant	Ant-Har	Average
Pioneer 27	0.0020a	0,0045a	0.0030a	0,0025a	0.0030a
Bisma	0.0018b	0.0042b	0.0029b	0.0023b	0.0028b

Note: Numbers followed by the same letter in the same column are not significantly different based on the t-test at α = 5%. (Eme=emergence, MaxVeg=maximum vegetative, Ant=anthesis, Har=harvest).

The Pioneer 27 variety showed higher SLA values at each development phase than Bisma. The SLA value can describe the leaf area in capturing light and CO_2 in biomass formation which is influenced by radiation interception and light use efficiency (Zhou et al.., 2020).

The amount of photosynthetic flow in the form of carbohydrates that enters each organ is determined by the magnitude of the carbohydrate partition coefficient. Carbohydrates allocated to each organ are used as energy for growth and maintenance (Ning et al., 2018). The results of measuring the carbohydrate partition coefficient as a growth model constant are listed in Table 4.

The carbohydrate partition coefficient varies for each variety at each developmental phase. Table 4 shows that the cob partition for the harvest phase is 69% for the Pioneer 27 and 52% for the Bisma variety. A greater cob partition value indicated greater biomass accumulation in the cob in the Pioneer 27 variety. Carbohydrates allocated to each organ are used for organ growth and maintenance through the respiration process (Julius et al., 2017).

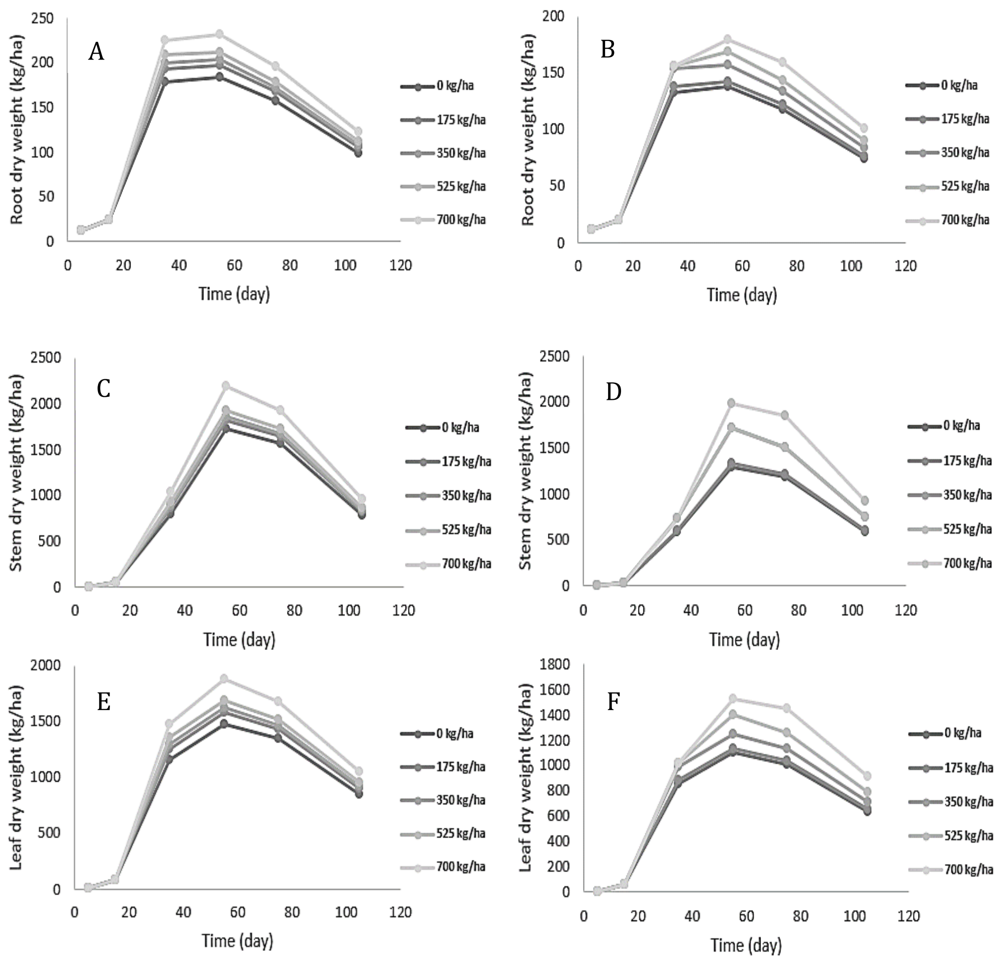
Table 4. Carbohydrate partition coefficient in four development phases of Bisma and Pioneer 27 corn varieties.

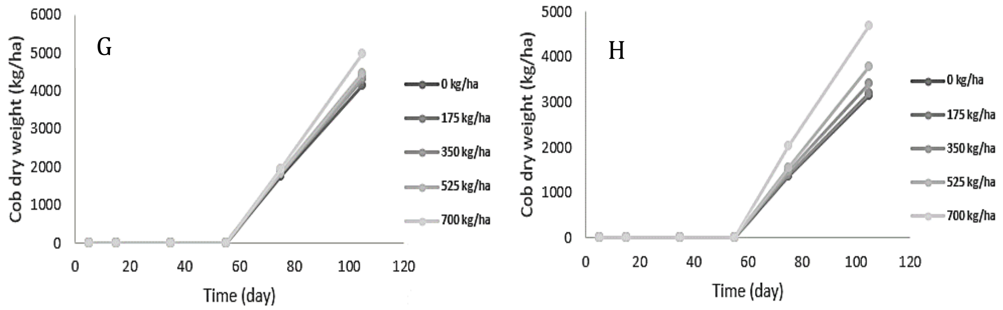
Variety	Plant-Eme	Eme-MaxVeg	MaxVeg-Ant	Ant-Har
		Root		
Pioneer 27	0.68a	0.16a	0.09b	0.05b
Bisma	0.62b	0.12b	0.11a	0.07a
		Leaf		
Pioneer 27	0.12a	0.29b	0.32b	0.18b
Bisma	0.11b	0.42a	0.39a	0.22a
		Stem		
Pioneer 27	0.20b	0.55a	0.58a	0.11b
Bisma	0.27a	0.46b	0.50b	0.19a
		Cob		
Pioneer 27	0.00	0.00	0.00	0.69a
Bisma	0.00	0.00	0.00	0.52b

Note: Numbers followed by the same letter in the same column are not significantly different based on the t-test at α = 5%. (Eme=emergence, MaxVeg=maximum vegetative, Ant=anthesis, Har=harvest).

Model simulation

The simulation results of the growth model corn varieties based on total dry weight are presented in Figure 2.





Note: A = Root dry weight P27, B = Root dry weight Bisma, C = Stem dry weight P27, D = Stem dry weight Bisma, E = Leaf dry weight P27, F = Leaf dry weight Bisma, G = Cob dry weight P27, H = Cob dry weight Bisma.

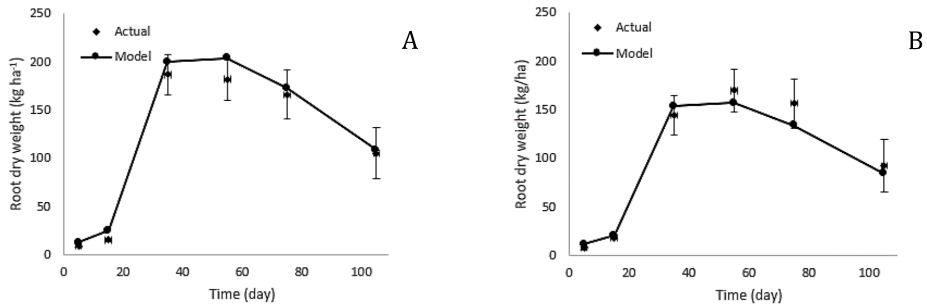
Figure 2. Simulation results of dry weight of corn plants of Pioneer 27 and Bisma varieties at different urea levels.

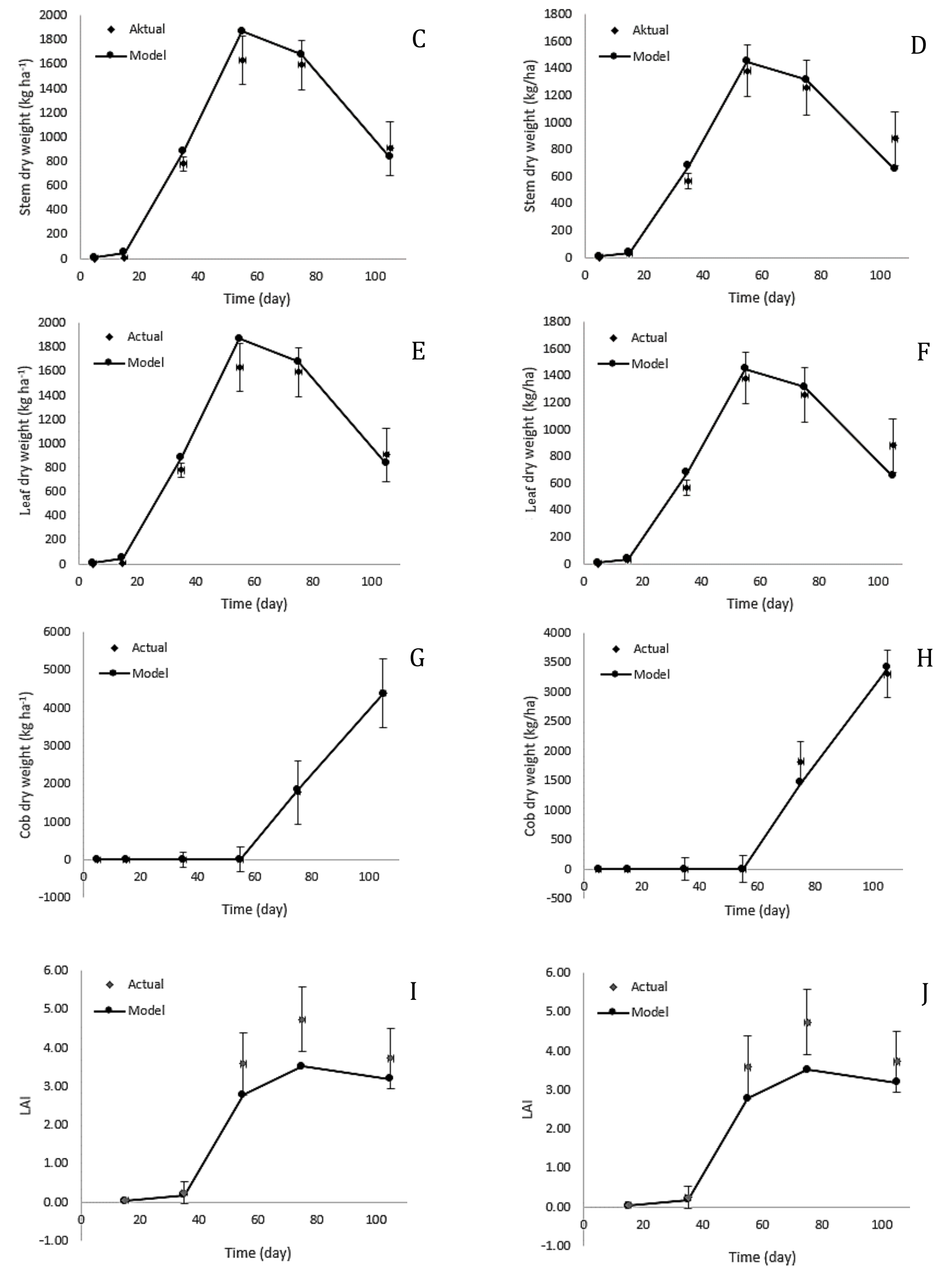
The difference in dry weight between doses of nitrogen shows differences in nitrogen accumulation between treatments which causes an increase in the total dry weight of the plant as the dose of nitrogen fertilizer is added (Sirappa & Nurdin, 2020). The differences in dry weight between varieties was influenced by the diversity of model input component values for each variety, where the values of light use efficiency, blackout coefficient, and specific leaf area for the Pioneer 27 tended to be higher than for the Bisma variety. Moelyohadi (2018) revealed that the Pioneer 27 variety has higher growth and corn production than Bisma due to different genetic backgrounds with greater growth rates and adapt to low soil nutrients.

Model validation

Model validation was carried out by comparing the actual observations and simulation models. The validation results are presented in Figure 3.

The dry weight value of corn plant organs for both varieties mostly had a validity level above 80% (Figure 3). This explains that some of the simulation results were almost the same as the actual results and the model built is able to describe corn growth and production at the recommended nitrogen fertilizer dose (350 kg ha^{-1}). The simulation model was declared valid because the dry weight value of the plant partition and the LAI value from the simulation results are within the standard deviation interval of the actual observation results. The results showed that the level of validity of the growth model for the Pioneer 27 variety reached 85.3% and for the Bisma variety 80%.





Note: A = Root dry weight P27, B = Root dry weight Bisma, C = Stem dry weight P27, D = Stem dry weight Bisma, E = Leaf dry weight P27, F = Leaf dry weight Bisma, G = Cob dry weight P27, H = Cob dry weight Bisma, I = Leaf area index value P27, J = Leaf area index value Bisma.

Figure 3. Validation results of dry weight and leaf area index estimates of Pioneer 27 and Bisma varieties between the actual and simulation model.

CONCLUSIONS

Simulation models of growth and nitrogen uptake of corn varieties Pioneer 27 and Bisma on the dry weight of roots, stems, leaves, and cobs were concluded using the Stella program. The model input considered light use efficiency, extinction coefficient, specific leaf area, and carbohydrate partition coefficient. The actual total plant dry weight for the Pioneer 27 was 6,406 kg ha^{-1} while the simulation resulted in 6,228 kg ha^{-1}. For Bisma, the actual total plant dry weight was 5,127 kg ha^{-1} while the simulation resulted in 4,864 kg ha^{-1}. The validity level of the growth model for the Pioneer 27 reached 83.5%, while for the Bisma reached 80%.

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