HortScience 60(5):715–723. 2025. https://doi.org/10.21273/HORTSCI18060-24

Impacts of Fertilization Regimes on Cabbage Growth Based on the CROPGRO Model

Jianchao Liu

Jiyang College of Zhejiang A & F University, Zhuji 311800, Zhejiang, China; College of Energy and Power Engineering, Lanzhou University of Technology, Lanzhou 730050, China; Postdoctoral Research Station, Jinyun Zhejiang University Science and Technology Agricultural Demonstration Base Co., Ltd., Jinyun 321400, Zhejiang, China; and Zhuji City Economic Specialty Station of Zhejiang Province, Zhuji 311800, Zhejiang, China

Jinping Li

College of Energy and Power Engineering, Lanzhou University of Technology, Lanzhou 730050, China

Kan Lv

Postdoctoral Research Station, Jinyun Zhejiang University Science and Technology Agricultural Demonstration Base Co., Ltd., Jinyun 321400, Zhejiang, China

Dan He

Zhuji City Economic Specialty Station of Zhejiang Province, Zhuji 311800, Zhejiang, China

Keywords. cabbage, CROPGRO model, fertilization regimes, optimization, simulation analysis

Abstract. **Effective fertilization management is crucial for enhancing the yield and quality of cabbage (*Brassica oleracea* L.). This study uses the CROPGRO model, calibrated with field data from 2021 and validated using 2022–23 data, to determine optimal fertilization regimes. The simulations reveal that nitrogen applications of 180 to 220 kg·hm^{-2} are ideal for maximizing head weight, whereas 300 kg·hm^{-2} of nitrogen is optimal for protein content, and 100 to 140 kg·hm^{-2} for the best harvest index. The most effective fertilization strategy involves applying 210 kg·hm^{-2} of nitrogen, along with 105 kg·hm^{-2} of phosphorus and 210 kg·hm^{-2} of potassium, during the seedling and maturity stages. This regime enhances nutrient use efficiency and supports sustainable agricultural practices.**

In 2022, global production of cabbage (*Brassica oleracea* L.) reached ∼71 million metric tons, highlighting its significant economic value and importance in the agricultural sector (FAO 2023). Efficient management of fertilization is crucial to enhance yields, improve nutritional quality, and promote sustainable agricultural practices (Momesso et al. 2022). This study focused on optimizing fertilization regimes to meet rising global demand, offering insights that could enhance economic gains and promote sustainable farming techniques.

Recent research has concentrated on refining fertilization management practices to boost cabbage yields and quality, while also reducing environmental impacts (Goswami et al. 2024). Al-Solimani (2004) noted that appropriate nitrogen application can significantly enhance cabbage yield and leaf nitrogen levels, whereas excessive use contributes to nitrogen loss and environmental pollution. Similarly, Liang et al. (2021) found that split applications of nitrogen improve both nitrogen use efficiency and yields over single applications.

These studies emphasize the need for carefully designed fertilization regimes that address the specific nutrient requirements of cabbage at various growth stages (Sun et al. 2022). Although these field experiments offer valuable insights, they are labor-intensive, time-consuming, and constrained by spatial and temporal variability (Mariotti et al. 2012). Keating et al. (2003) used the Agricultural Production Systems Simulator (APSIM) to develop fertilization protocols. APSIM's dynamic simulation capabilities enabled evaluation of various nutrient management regimes, taking into account factors like soil type, weather patterns, and crop needs. Sharpley and Williams (1990) used the Environmental Policy Integrated Climate (EPIC) model to assess how different fertilization regimes affect crop yield and soil health. The comprehensive approach of the EPIC model, including aspects like soil erosion, hydrology, and nutrient cycling, offered insights into the long-term sustainability of various fertilization practices. Übelhör et al. (2015) calibrated and evaluated the CROPGRO cabbage model under temperate European climate conditions, confirming its effectiveness in predicting yields for various management regimes. Initially developed for legumes, the CROPGRO model—part of the Decision Support System for Agrotechnology Transfer (DSSAT)—has expanded to include crops like bell peppers, cabbage, tomatoes, sweet corn, and green beans (Boote et al. 1998). This model is capable of simulating various scenarios based on climate, soil, and environmental conditions, including crop responses to different fertilizers and irrigation regimes.

Research on cabbage fertilization has traditionally depended on field experiments, which are labor-intensive, time-consuming, and prone to variability. To address these challenges, advanced crop models such as CROPGRO simulate a broad spectrum of fertilization scenarios more efficiently (Boote et al. 1998). Nonetheless, a significant gap persists in the comprehensive application of these models. This underutilization results in suboptimal fertilization practices, decreased yields, inefficient nutrient utilization, and potential environmental harm.

This study addresses traditional fertilization strategy shortcomings by using the CROPGRO model to optimize fertilization regimes for cabbage cultivation. Unlike labor-intensive field experiments, the CROPGRO model efficiently simulates various management scenarios, predicting outcomes for diverse fertilization regimes. This method improves nutrient use efficiency, increases yields, and reduces environmental impacts. The study concentrates on calibrating the model, validating it with field data, and devising optimized fertilization protocols. The research illustrates the model's potential to enhance sustainable cabbage production.

Materials and Methods

Experimental site. Field experiments were carried out at the agricultural research station in Zhuji, Zhejiang Province, China, spanning the 2021 to 2023 growing seasons. Zhuji lies within a subtropical monsoon climate zone. The area receives an average annual precipitation of 1500 mm and maintains an average temperature of 16 °C. Monthly temperatures vary from 4 °C in January to 28 °C in July. The area receives ∼2000 h of sunshine annually. Experimental plots were established on loamy soil characterized by well-defined layers. The topsoil, extending 0 to 20 cm deep, is rich in organic matter and exhibits a bulk density of 1.25 g·cm^{-3}, containing 120 mg·kg^{-1} nitrogen, 30 mg·kg^{-1} phosphorus, and 200 mg·kg^{-1}

Received for publication 2 Jul 2024. Accepted for publication 5 Dec 2024.

Published online 2 Apr 2025.

We are grateful for the financial support provided by China Postdoctoral Science Foundation (348728), Shaoxing Doctor Innovation Station Fund (20220623), and the 111 Project of the Ministry of Education and the State Administration of Foreign Experts Affairs (B12007).

D.H. is the corresponding author. E-mail: 85268173@qq.com.

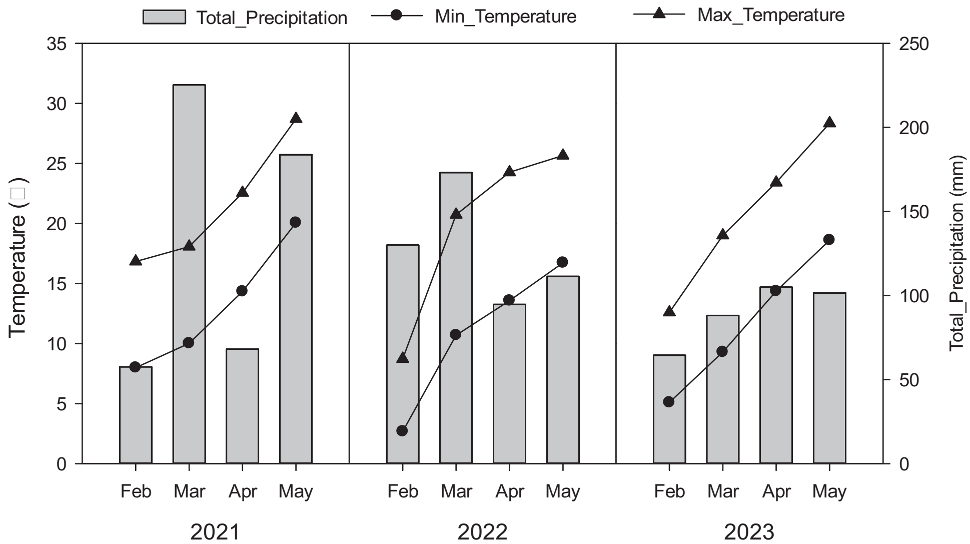

Fig. 1. Monthly total precipitation, minimum temperature, and maximum temperature at the experimental site from 2021 to 2023.

potassium, with 3.5% organic matter content. The subsoil layer, 20 to 40 cm deep, features a bulk density of 1.35 $g\cdot cm^{-3}$ and comprises 80 $mg\cdot kg^{-1}$ nitrogen, 20 $mg\cdot kg^{-1}$ phosphorus, 150 $mg\cdot kg^{-1}$ potassium, and 2.0% organic matter. In the deeper layer, 40 to 60 cm beneath the surface, the soil has a bulk density of 1.40 $g\cdot cm^{-3}$ and contains 60 $mg\cdot kg^{-1}$ nitrogen, 15 $mg\cdot kg^{-1}$ phosphorus, and 100 $mg\cdot kg^{-1}$ potassium, with an organic matter percentage of 1.5%.

Over 3 years, the average minimum temperature rose each month from February to May (Fig. 1). Precipitation levels varied annually over the 3-year period. In 2021, March saw the highest precipitation, at 225.3 mm, with lower levels in other months. Although adequate March precipitation aids cabbage growth by providing necessary moisture, excessive rainfall can waterlog soils, adversely affecting root respiration and nutrient uptake. In 2022, February experienced higher precipitation at 130.0 mm, with lower amounts following in subsequent months. This pattern provides sufficient water in early spring but may necessitate supplementary irrigation during peak growth periods, such as May, to ensure optimal moisture availability. The 2023 precipitation was more evenly distributed, peaking in May with 158.2 mm. Consistent rainfall throughout the growing season supports steady water availability, reducing drought stress risks on cabbage.

Experimental design. Over 2 years, the study evaluated eight different fertilization regimes for cabbage (*Brassica oleracea* var. capitata). Treatments were divided into high (21HF, 22HF, 23HF), medium (22MF, 23MF), and low (22LF, 23LF) fertilization levels, and severe nitrogen stress (230F). All treatments used the ‘Jinqiu’ variety of cabbage. Each treatment varied in the application of nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O), along with the number of fertilization events. Table 1 presents detailed information about the treatments, including seeding, transplanting, and harvest dates.

This study assessed cabbage growth and nutritional quality across various fertilization treatments. Key indicators, including head yield, protein content, leaf number, nitrogen content, leaf area index, tops weight, and harvest index, were measured and are detailed in Table 2. These measurements aimed to evaluate how different fertilization rates and frequencies affect cabbage growth and quality.

Model description. CROPGRO, a process-oriented model, simulates daily plant growth by integrating the dynamics of crop carbon, soil water, and soil nitrogen. The model necessitates daily weather data—including temperatures, precipitation, and solar radiation—and soil physical and chemical properties, along with crop management details and genotype information. The model produces daily predictions of plant dry matter, leaf area index, canopy development, and movements of soil water and salts, while also assessing water and nitrogen stress and tracking phenological stages. Within the model, the cabbage head is depicted as a “pod,” with its development classified as a generative organ. In CROPGRO, the stem is categorized as a vegetative organ for both cabbage and Chinese cabbage, even though it is part of the economically important tissue of the head. Only the cabbage head’s leaves are considered part of the pod. The model calculates the net pod growth rate as the sum of the shell and seed growth rates.

$$WPDOT = WSHDOT + WSDDOT, \quad [1]$$

where WSHDOT is Net shell growth rate ($g\cdot m^{-2}\cdot d^{-1}$ shell)($g\cdot m^{-2}\cdot d^{-1}$ shell); WSDDOT is Net seed growth rate ($g\cdot m^{-2}\cdot d^{-1}$ shell) ($g\cdot m^{-2}\cdot d^{-1}$ shell).

$$WSHDOT = WSHDTN - WSHIDT - WTABRT - NRUSSH/0.16 - CRUSSH \quad [2]$$

where WSHDTN is the new shell growth today ($g\cdot m^{-2}\cdot d^{-1}$ shell)($g\cdot m^{-2}\cdot d^{-1}$ shell),

Table 1. Fertilization treatments and key dates for cabbage cultivation from 2021 to 2023.

Treatment	N ($kg\cdot hm^{-2}$)	P_2O_5 ($kg\cdot hm^{-2}$)	K_2O ($kg\cdot hm^{-2}$)	Seeding date	Transplanting date	Harvest date
21HF	203.85	105.75	254.25	15 Jan 2021	24 Feb 2021	28 Apr 2021
22HF	67.95	35.25	84.75	8 Feb 2022	14 Mar 2022	23 May 2022
22MF	135.9	70.5	169.5	8 Feb 2022	14 Mar 2022	23 May 2022
22LF	203.85	105.75	254.25	8 Feb 2022	14 Mar 2022	23 May 2022
23HF	0	0	0	6 Feb 2023	12 Mar 2023	23 May 2023
23MF	105	39.9	15.162	6 Feb 2023	12 Mar 2023	23 May 2023
23LF	210	79.8	30.324	6 Feb 2023	12 Mar 2023	23 May 2023
230F	315	119.7	45.486	6 Feb 2023	12 Mar 2023	23 May 2023

This table summarizes the fertilization treatments and key dates for cabbage cultivation over three growing seasons (2021, 2022, and 2023) at the Zhuji research station. Each treatment is identified by its year and level of fertilization (HF = high fertilization, MF = medium fertilization, LF = low fertilization, 0F = zero fertilization).

Table 2. Comprehensive measurement parameters for cabbage growth assessment.

Measurement indicator	Measurement frequency	Measurement method
Soil moisture	Hourly automatic checks	Tube soil moisture monitor (RS-WS-N01-TR-6, Shandong Renke Control Technology Co., Ltd.) for soil volume water content every 10 cm up to 1.0 cm depth.
Air temperature	Hourly automatic checks	Air temperature sensor (RSFE-BYH-M, Shandong Renke Control Technology Co., Ltd.).
Light intensity	Hourly automatic checks	Light intensity sensor (RSFE-WS-N01-TR-1, Shandong Renke Control Technology Co., Ltd.).
CO_2 concentration	Hourly automatic checks	CO_2 concentration sensor (RSFE-QXZ-M, Shandong Renke Control Technology Co., Ltd.).
Soil nutrients	Every 14 d	Layered measurement of soil inorganic nitrogen, organic matter, and total nitrogen content every 10 cm up to 60-cm depth.
Tops weight	Every 7 d	Sampling five plant samples per plot, drying at 75 °C until constant weight, and recording dry weight of different organs.
Head yield	At harvest	Ten heads are selected per plot, dried at 75 °C until constant weight. Average dry weight per head is calculated and multiplied by the number of plants per hectare to determine yield.
Head protein content	At harvest	Protein content is determined using the Kjeldahl method with a JELTEC 2300 apparatus (Sweden FOSS).
Canopy height	Every 7 d	Distance from the base of the plant at the ground to the highest point of the plant.
Canopy width	Every 7 d	Maximum natural spread distance of the outer leaves of the plant.
Leaf length	Every 7 d	Length from the base of the wing of the largest leaf to the tip of the leaf.
Leaf width	Every 7 d	Width at the widest part of the largest outer leaf.

representing the daily increase in shell mass due to growth; WSHIDT is the weight of shell tissue consumed by pests today ($g{\cdot}m^{-2}{\cdot}d^{-1}$ shell)($g{\cdot}m^{-2}{\cdot}d^{-1}$ shell), indicating the reduction in shell mass due to pest activity; WTABRT is the weight of shells aborted on a day ($g{\cdot}m^{-2}{\cdot}d^{-1}$ shell)($g{\cdot}m^{-2}{\cdot}d^{-1}$ shell), accounting for the shell mass lost due to abortion; NRUSSH is the nitrogen actually mobilized from shells in a day ($g{\cdot}m^{-2}{\cdot}d^{-1}$ N) ($g{\cdot}m^{-2}{\cdot}d^{-1}$ N), representing the amount of nitrogen relocated from the shell to other parts of the plant; and CRUSSH is the carbon mobilized from shell tissue in a day ($g{\cdot}m^{-2}{\cdot}d^{-1}$ CH_2O).

$$WSDDOT = WSDDTN - SWIDOT \qquad [3]$$

where WSDDTN is the new seed growth today ($g{\cdot}m^{-2}{\cdot}d^{-1}$ seed)($g{\cdot}m^{-2}{\cdot}d^{-1}$ seed), representing the daily increase in seed mass due to growth; and SWIDOT is the daily seed mass damage ($g{\cdot}m^{-2}{\cdot}d^{-1}$)($g{\cdot}m^{-2}{\cdot}d^{-1}$), indicating the reduction in seed mass due to various damaging factors.

Model evaluation. In 2022 and 2023, models were evaluated by comparing observed and simulated data for variables such as leaf area index (LAI), leaf number, tops weight, head yield, and head protein content. Fertilization treatments varied for spring cabbage in Zhuji, Zhejiang Province, to validate model predictions across different nutrient management scenarios. Model accuracy was assessed using three indicators: deviation ratio (d), relative root mean square error (RRMSE), and a comparison of observed vs. simulated values. A lower deviation ratio indicates higher accuracy of simulated results. RRMSE, a unit-independent measure of homogenization error, indicates accuracy; smaller values signify minor differences between observed and simulated data. The evaluation criteria for RRMSE are 0 to 0.1 (excellent), 0.1 to 0.2 (good), 0.2 to 0.3 (fair), and >0.3 (poor).

$$d = \frac{s_i - o_i}{o_i} \times 100\% \qquad [4]$$

$$RRMSE = \frac{\sqrt{\sum_{i=1}^{n} \frac{(s_i - o_i)^2}{n}}}{\sum_{i=1}^{n} \frac{o_i}{n}} \times 100\% \qquad [5]$$

where s_i is the simulated value, o_i is the observed value, and n is the sample size.

Optimization principle of fertilization management. This study designed fertilization treatments to explore the effects of varying nitrogen (N), phosphorus (P), and potassium (K) application rates and schedules on cabbage growth using the CROPGRO model. Nitrogen fertilization was applied in a range from 0 to 400 $kg{\cdot}hm^{-2}$ in 10-kg increments. The N:P_2O_5:K_2O ratio was consistently maintained at 2:1:2. Fertilization frequency ranged from 0 to 4, targeting specific growth stages: seedling (S), rosette (R), heading (H), and maturity (M). The total number of possible fertilization treatments, 3280, was calculated based on various combinations of these variables. Specifically, the study considered 41 levels of nitrogen application (including 0 kg), five fertilization frequencies, and 16 combinations of four growth stages.

The Treatment ID specifies the amounts of nitrogen (N), phosphorus (P), and potassium (K) applied, the number of fertilization events, and the growth stages (S, R, H, M) at which fertilization was applied. Binary coding (0 and 1) represents various fertilization stage combinations; "1001" signifies fertilization at the seedling and maturity stages. For example, "F50T1001" denotes a treatment with 50 $kg{\cdot}hm^{-2}$ nitrogen, 25 $kg{\cdot}hm^{-2}$ phosphorus, and 50 $kg{\cdot}hm^{-2}$ potassium, applied twice at both the seedling and maturity stages. All treatments used the calibrated CROPGRO model, leveraging 30 years of weather data (1984–2013) to simulate cabbage head yield and leaf nitrogen content. The outputs, head yield and head nitrogen content, function as optimization criteria for fertilization regimes. Optimal fertilization regimes were determined using key performance indicators including head yield, head protein content, and harvest index. Criteria for selecting optimal practices include

$$\begin{cases} \overline{Head\ Yield} \geq 90\% Head\ Yield_{\mathrm{Max}} \\ \overline{\text{Harvest index}} \geq 90\%\text{Harvest index}_{\mathrm{Max}} \\ \overline{\text{Head protein content}} \geq 80\%\text{Head protein content}_{\mathrm{Max}} \end{cases} \qquad [6]$$

where head yield is the dry matter weight of cabbage heads, $kg{\cdot}hm^{-2}$; Head protein content is the percentage of protein in the cabbage heads, %; Harvest index is ratio of head yield to total aboveground biomass, %. $\overline{Head\ Yield}$ is the average simulated multiyear head yield, $kg{\cdot}hm^{-2}$; $Head\ Yield_{\mathrm{Max}}$ is the maximum simulated head yield, $kg{\cdot}hm^{-2}$.

Results

Model calibration

The CROPGRO model was calibrated using data from a 2021 high-fertilization treatment of spring cabbage (Table 3). This experiment took place in Zhuji, Zhejiang Province. Simulated values from the CROPGRO model were compared with observed values to evaluate performance.

For head yield, the simulated value was 4971 $kg{\cdot}hm^{-2}$ compared with an observed 5036 $kg{\cdot}hm^{-2}$, showing a deviation of 1.31% and indicating good model accuracy. The simulated head protein content was 26.625% vs. the observed 29.562%, a deviation of 9.94%, indicating a moderate discrepancy.

Table 3. Calibration of the CROPGRO model using 2021 spring cabbage fertilization treatment.

Head yield ($kg{\cdot}hm^{-2}$)			Head protein content (%)			Leaf number			Canopy ht (m)		
s_i	o_i	d (%)	s_i	o_i	d (%)	s_i	o_i	d (%)	s_i	o_i	d (%)
4971	5036	1.31	26.625	29.562	9.94	17	19	10.53	0.234	0.231	−1.30

The simulated values (s_i) generated by the model are compared with the observed values (o_i), and the deviation percentages (d/%) are calculated to assess the model's accuracy.

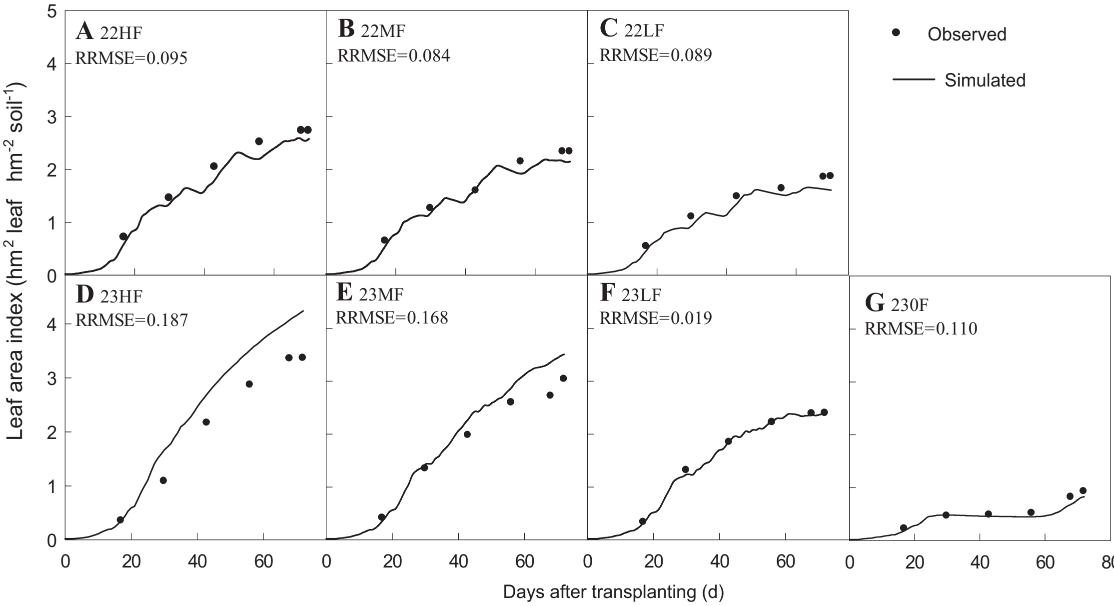

Fig. 2. Comparison of observed and simulated leaf area index (LAI) for cabbage under different fertilization treatments in 2022 and 2023. Each subplot shows the LAI as a function of days after transplanting, with dots representing observed values and lines representing simulated values. The relative root mean square error (RRMSE) is indicated for each treatment to quantify the model's accuracy.

Simulated leaf count was 17 and the observed count was 19, resulting in a 10.53% deviation. Canopy height was simulated at 0.234 m, compared with an observed 0.231 m, a deviation of −1.30%. The CROPGRO model demonstrated high accuracy in predicting head yield and canopy height, as evidenced by low deviation percentages for the 2021 high-fertilization treatment of spring cabbage. Moderate discrepancies in predicted head protein content and leaf number indicate areas for further refinement and calibration of the model. Overall, the model performs effectively, providing reliable simulations across most parameters.

Model evaluations

These experiments in 2022 and 2023 involved various fertilization treatments applied to spring cabbage to validate the model's predictions under different fertilization regimes. The key parameters measured included LAI, leaf number, tops weight, and head yield. The model evaluations for 2022 and 2023 confirmed that the CROPGRO model is a valuable tool for optimizing fertilization regimes and improving crop management practices in cabbage cultivation.

LAI. Under high fertilizer treatments, the model tends to underestimate LAI growth (Fig. 2A and D). In medium fertilizer treatments, the model demonstrates improved predictive accuracy (Fig. 2B and E). The RRMSE values, 0.084 for 22MF and 0.168 for 23MF, reflect closer alignment with observed values, particularly under medium nitrogen conditions. The model excels in low nitrogen scenarios, as evidenced by strong predictive performance in low fertilizer treatments (Fig. 2C and F). The zero-fertilizer treatment (230F) shows the largest prediction error, with an RRMSE of 0.110 (Fig. 2G). The significant prediction discrepancy underlines challenges in simulating LAI growth in conditions of extreme nitrogen deficiency, necessitating further optimization of model

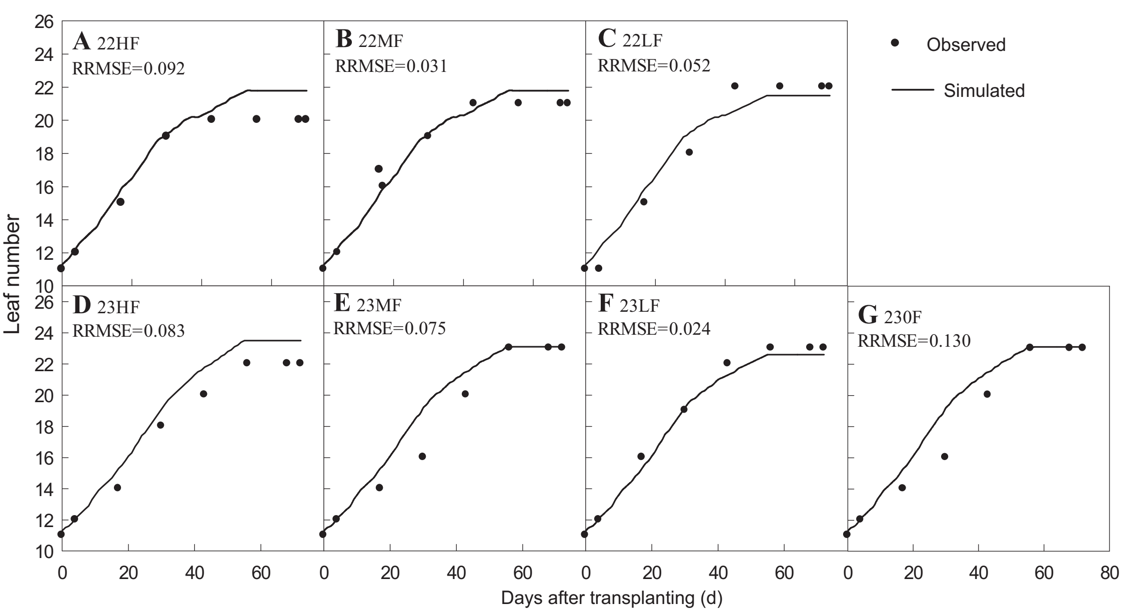

Fig. 3. Comparison of observed and simulated leaf number for cabbage under different fertilization treatments in 2022 and 2023. Each subplot shows the number of leaves as a function of days after transplanting, with dots representing observed values and lines representing simulated values. The relative root mean square error (RRMSE) is indicated for each treatment to quantify the model's accuracy.

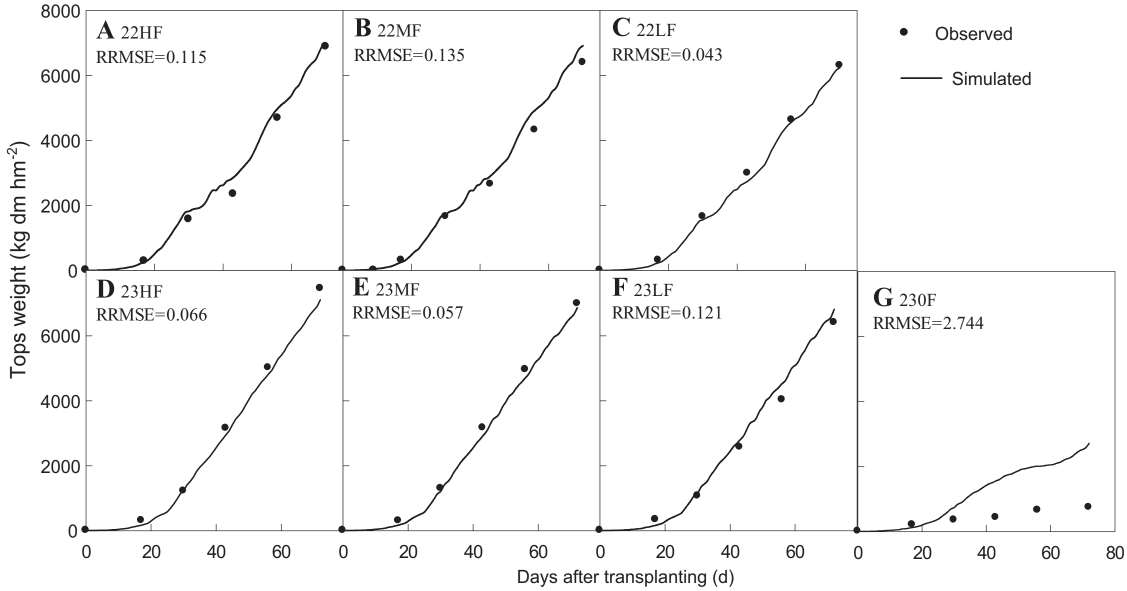

Fig. 4. Comparison of observed and simulated tops weight for cabbage under different fertilization treatments in 2022 and 2023. Each subplot shows the tops weight as a function of days after transplanting, with dots representing observed values and lines representing simulated values. The relative root mean square error (RRMSE) is indicated for each treatment to quantify the model's accuracy.

parameters. Overall, the CROPGRO model demonstrates varying degrees of accuracy in simulating LAI for cabbage under different nitrogen treatments.

Leaf number. In the 22HF treatment, simulated leaf counts consistently exceeded actual measurements, yielding an RRMSE of 0.092 (Fig. 3A). This overestimation persists through the growth period, notably in later stages, suggesting the model exaggerates leaf growth under high nitrogen conditions. Similarly, for 22LF and 230F, RRMSEs of 0.052 and 0.13, respectively (Fig. 3C and G), indicate the model's propensity to overpredict leaf growth in low and zero nitrogen scenarios. In the 22MF and 23MF treatments, minor discrepancies between simulated and observed leaf numbers feature RRMSEs of 0.031 and 0.075, respectively (Fig. 3B and E). The lower RRMSEs suggest improved model accuracy under medium nitrogen conditions, likely due to better-calibrated parameters enhancing simulation precision. The 23HF and 23LF treatments display higher simulated than observed leaf counts, though with reduced errors (RRMSEs of 0.083 and 0.024) compared with 2022 (Fig. 3D and F). Especially in early growth stages, closer alignment between simulated and actual values in 2023 demonstrates enhanced model adaptability and prediction accuracy. The 230F treatment exhibits the most significant simulation error with an RRMSE of 0.13, highlighting substantial discrepancies, particularly in later stages (Fig. 3G).

Tops weight. For the 2022 high fertilizer treatment (22HF), the model's simulated biomass closely matched the measured values, demonstrating robust performance with an RRMSE of 0.115 (Fig. 4A). The medium fertilizer treatment (22MF) also showed reasonable accuracy, with an RRMSE of 0.135 (Fig. 4B), whereas the low fertilizer treatment (22LF) achieved the best performance, indicated by the lowest RRMSE of 0.043, exemplifying excellent model precision (Fig. 4C).

The 23HF treatment showed an RRMSE of 0.066, indicating good alignment between the simulated and observed data (Fig. 4D). The 23MF treatment consistently demonstrated solid performance with an RRMSE of 0.057 (Fig. 4E). However, the 23LF treatment exhibited increased variability with an RRMSE of 0.121, still considered within an acceptable range despite being higher than in the previous year (Fig. 4F). The 230F treatment recorded the largest discrepancy with an RRMSE of 2.744, reflecting significant limitations in the model's accuracy under conditions of no fertilization (Fig. 4G).

Overall, the CROPGRO model has demonstrated a strong capability in simulating cabbage biomass across various fertilization treatments, with most achieving low RRMSE values that signify good to excellent performance. The notable exceptions in zero fertilization scenarios underscore areas needing refinement. This variability and the consistent performance across different fertilization levels and years underscore the model's potential utility for agricultural biomass prediction and management.

Head yield. The 22HF treatment demonstrated close alignment between the simulated and measured head yields, showcasing the model's robust performance under high-fertilization conditions (Fig. 5). Similarly, the 23HF and 23MF treatments exhibited high accuracy in their predictions, confirming the effectiveness of the model. Although the 22HF and 22MF treatments displayed some discrepancies, their overall performance was satisfactory.

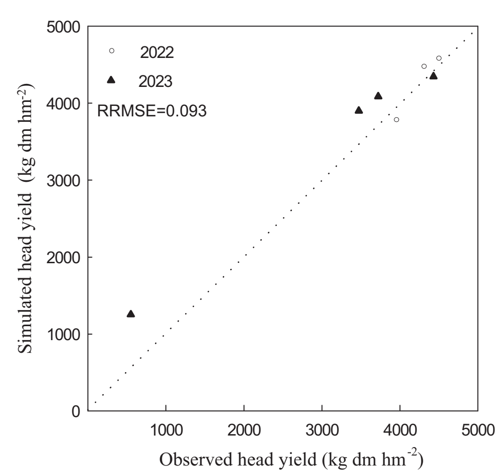

Fig. 5. Comparison of observed and simulated head yield for cabbage in 2022 and 2023. The dotted line represents the 1:1 line, where points falling on this line indicate perfect agreement between observed and simulated values. The relative root mean square error (RRMSE) is provided as a measure of model accuracy.

However, under severe nitrogen stress conditions (230F), significant deviations between the simulated and observed values highlighted the model's limitations in accurately predicting yields in extreme scenarios.

Overall, the CROPGRO model displayed excellent predictive capabilities for cabbage head yield across various fertilization treatments. Despite its strong performance across different fertilization levels and over several years, the model revealed some deficiencies under severe nitrogen stress, pointing to areas for further refinement. The consistent performance across diverse scenarios emphasizes the model's utility as a valuable tool in agricultural production forecasting.

Head protein content. The results indicate that the model's simulated values for head protein content are closely aligned with the measured values across all seven treatments (Fig. 6). This high level of accuracy, with a RRMSE of 0.112, demonstrates the model's effectiveness in predicting head protein content under varied fertilization regimes. These findings underscore the model's applicability in optimizing agricultural fertilization management and enhancing crop performance forecasting.

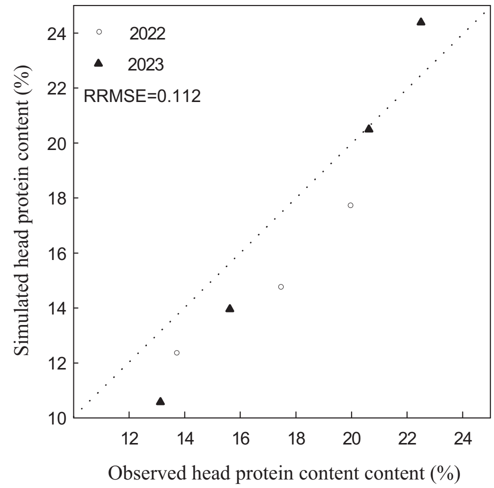

Fig. 6. Comparison of observed and simulated head protein content for cabbage in 2022 and 2023. Each point represents a specific treatment, with circles indicating data from 2022 and triangles representing data from 2023. The dotted line represents the 1:1 line, where points falling on this line indicate perfect agreement between observed and simulated values. The relative root mean square error (RRMSE) is provided as a measure of model accuracy, with a value of 0.112 indicating good model performance.

Simulation of fertilization regimes

Increasing fertilization amounts generally enhance cabbage head yields across all schedules, peaking and then plateauing or slightly declining as levels approach 300 kg·hm^{-2} (Fig. 7). Enhanced yields are particularly notable with more frequent fertilization events, up to four times, especially with lower to moderate nitrogen applications. The optimal nitrogen application for maximizing yields is observed between 180 and 220 kg·hm^{-2}, beyond which the benefits start to diminish due to diminishing returns.

The analysis reveals considerable variations in cabbage yields influenced by fertilization regimes (Fig. 8). Maximum yields are consistently associated with fertilization initiated at the seedling stage, either alone or in combination with other stages. In contrast, regimes omitting seedling stage fertilization typically yield lower outputs. Notably, combinations involving multiple stages, particularly those that include the seedling stage, are most effective in producing high yields.

Cabbage head protein content increases with the rate of fertilization, peaking at a rate of 300 kg·hm^{-2} before the rate of increase moderates (Fig. 9). In addition, more frequent fertilization events generally enhance protein content, with particularly notable benefits at lower fertilization rates. The data illustrate that regimes with three or four fertilization events yield higher protein levels than those with fewer. However, protein content tends to plateau at higher fertilization rates, suggesting diminishing returns with excessive fertilizer application. This analysis underscores the importance of both the rate and frequency of fertilization in optimizing protein content in cabbage heads.

The harvest index increases with the rate of fertilization, peaking at ∼100 to 140 kg·hm^{-2}, before it starts to decline (Fig. 10). Multiple fertilization events tend to yield a higher harvest index compared with singular or absent fertilization events, with the peak effect notably observed within this optimal range. Beyond this range, the harvest index decreases, suggesting that excessive fertilization surpasses the optimal threshold, thereby reducing harvest efficiency. This finding indicates that there is a precise range of fertilization that maximizes harvest index, highlighting the importance of calibrated fertilization practices in agricultural yield optimization.

Selection of optimal nitrogen fertilization regimes

These 14 fertilization treatments optimized head weight, head protein content, and harvest index (Table 4). In addition, the highest values recorded in the dataset were a head weight of 5218 kg·hm^{-2}, a head protein content of 23.95%, and a harvest index of 65.02%, suggesting potential for further optimization. Optimal nitrogen application rates varied from 210 to 240 kg·hm^{-2}, involving two to four fertilization events across different growth stages including seedling, rosette, heading, and maturity. The resulting head weights ranged from 4697 to 4870 kg·hm^{-2}, protein contents from 19.70% to 21.49%, and harvest indices from 58.55% to 60.96%. Among these, the F210T1010 treatment, applying 210 kg·hm^{-2} of nitrogen, 105 kg·hm^{-2} of phosphorus, and 210 kg·hm^{-2} of potassium in two events at the seedling and maturity stages, was particularly effective. It yielded a head weight of 4754 kg·hm^{-2}, a protein content of 20.35%, and a harvest index of 60.95%. This regimen not only maximized agronomic efficiency but also minimized

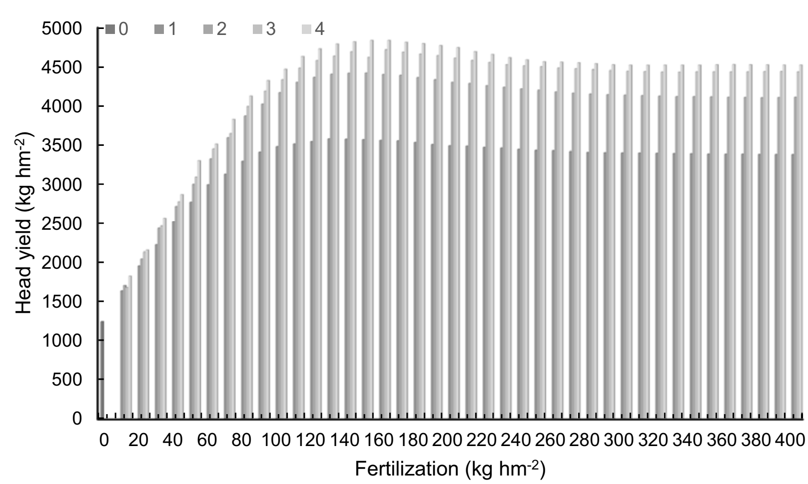

Fig. 7. The effect of different fertilization rates and frequencies on cabbage head yield. The different shades in the bars indicate the number of fertilization events, with numbers 0, 1, 2, 3, and 4 representing zero to four fertilization events, respectively.

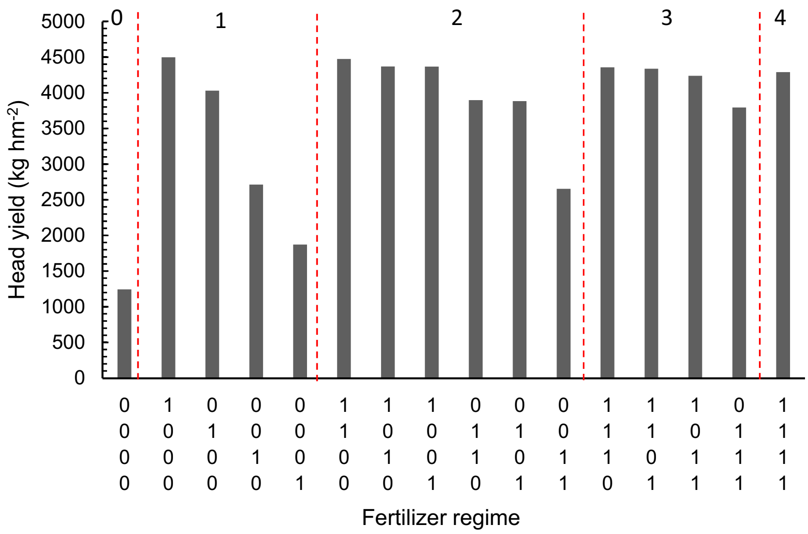

Fig. 8. Effect of different fertilization regimes on cabbage head yield. The possible fertilization stages include the seedling stage (S), rosette stage (R), heading stage (H), and maturity stage (M). The x-axis “Fertilizer regime” uses binary coding (0 and 1) to represent different combinations of fertilization stages; for instance, “1001” indicates fertilization during the seedling stage (S) and maturity stage (M). The y-axis represents cabbage head yield (kg·hm^{-2}). And the 0, 1, 2, 3, 4 represent zero, one, two, three, and four fertilization events, respectively. Red dashed lines mark the boundaries between different numbers of fertilization frequency.

labor, operational costs, and environmental impact, making it a sustainable choice for optimizing cabbage cultivation.

Discussion

This study underscores the vital role of fertilization management in enhancing cabbage growth, yield, and quality. Using the CROPGRO model, we simulated and assessed the impacts of various fertilization regimes on key growth parameters. Our findings provide insightful regimes for optimal cabbage cultivation, demonstrating the effectiveness of precise fertilization practices.

Model performance and limitations

The CROPGRO model exhibited robust performance in simulating essential growth parameters, including LAI, leaf number, head yield, and head protein content, particularly under moderate to high nitrogen conditions. These findings are consistent with the results reported by Jones et al. (2003) and Boote et al. (1998), who observed that the CROPGRO model consistently delivers accurate predictions under optimal or near-optimal nutrient conditions. In addition, the literature underscores the model’s effectiveness in estimating biomass and yield in scenarios where plants are not subjected to severe stress.

Although the model exhibited robust performance under moderate to high nitrogen conditions, its capability to simulate growth parameters under severe nitrogen stress proved limited (Ozfidan-Konakci et al. 2022). These discrepancies indicate that the current model parameters may not fully represent the physiological responses of plants to extreme nutrient deficiencies (Gao et al. 2016). Future research should aim to refine the model to enhance its precision under stress conditions. Enhancements could include incorporating more detailed physiological data and developing algorithms that more accurately simulate nutrient uptake and stress responses.

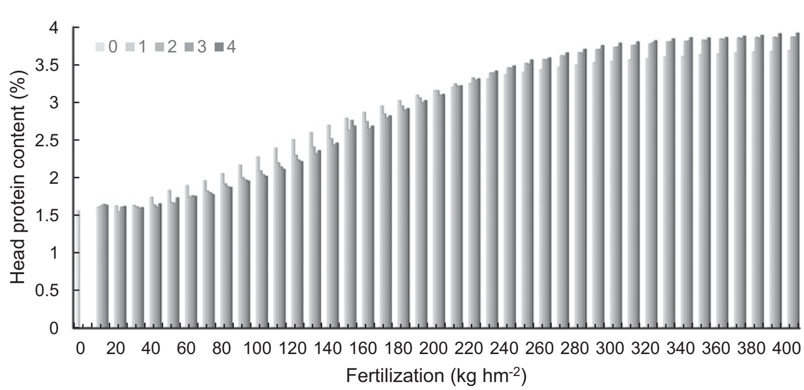

Fig. 9. The effect of different fertilization regimes on cabbage head protein content. The different shades in the bars indicate the number of fertilization events, with numbers 0, 1, 2, 3, and 4 representing zero to four fertilization events, respectively.

Simulation of fertilization regimes

Fertilization amount. The optimal fertilization rates to maximize head yield, protein content, and harvest index are ∼180 to 220 kg·hm^{-2}, 300 kg·hm^{-2}, and 100 to 140 kg·hm^{-2}, respectively. Beyond these levels, the benefits of additional nitrogen diminish. Coolong et al. (2022) have shown that optimal nitrogen application significantly enhances cabbage yield up to a threshold, beyond which yields plateau or decline due to potential nutrient imbalances or excessive vegetative growth. As nitrogen application increases, plant roots’ capacity to absorb nitrogen nears saturation, making further uptake challenging (Chun et al. 2005). Moderate nitrogen application optimizes biomass allocation toward economically important plant parts; however, excessive nitrogen may reduce harvest efficiency due to the overgrowth of vegetative parts (Huimin et al. 2020). A combination of factors including nutrient uptake saturation, imbalances, physiological stress, and environmental conditions, limits the efficacy of additional nitrogen, culminating in a plateau or decrease in yield response (Yang et al. 2023).

The CROPGRO model’s performance diminishes under severe stress due to its parameter sensitivity, as calibration tailored for mild stress does not reliably extrapolate to extreme conditions (Boote et al. 1998). Simplifications inherent in modeling stress responses often result in inaccuracies. For example, Ban et al. (2015) pointed out limitations in accurately simulating complex drought responses.

Fertilization frequency. A typical fertilization schedule includes three to four events per growing season. This frequency ensures continuous nutrient availability, promoting sustained growth, higher yields, and improved nutrient content. Importantly, it avoids the diminishing returns associated with more frequent fertilization. Split nitrogen application has been shown to significantly enhance cabbage yields compared with single or double applications, primarily due to improved nitrogen use efficiency and reduced losses from leaching and volatilization (Qu et al. 2019). Frequent nitrogen applications also increase the protein content in cabbage by ensuring adequate nitrogen availability during key stages of protein synthesis, thereby boosting overall protein accumulation (Zhen-Ming et al. 2013). Furthermore, split applications optimize the harvest index by ensuring a balanced nutrient distribution between vegetative and reproductive plant parts, improving biomass partitioning efficiency (Staugaitis et al. 2008).

Fertilization stages. Applying fertilizers at the seedling stage is crucial, as it provides young plants with essential nutrients necessary for initial growth. This early nutritional support is pivotal for establishing a robust root system and vigorous vegetative growth, which are indispensable for the plant’s later stages of development. According to Zhang et al. (2012), fertilization at the seedling

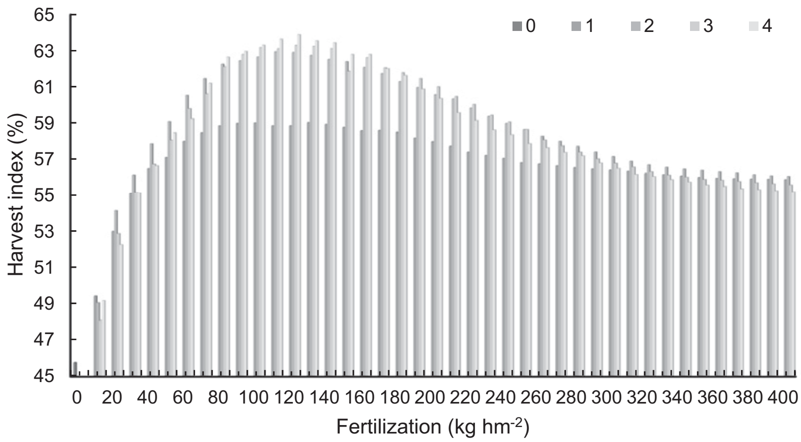

Fig. 10. Effect of different fertilization regimes on harvest index. The number of fertilization events varies from zero to four times, represented by different shades of gray.

and heading stages significantly enhances cabbage yields by ensuring the availability of nutrients during critical developmental phases.

Fertilization at the maturity stage has a negligible impact on cabbage yield. Ding et al. (2012) observed that applying nutrients during this phase does not enhance cabbage yield, emphasizing that nutrient absorption is crucial during the early to midgrowth stages. By the maturity stage, cabbage plants have largely completed their nutrient uptake, shifting their focus to head development. Consequently, fertilization at this later stage is ineffective, particularly if the plants did not receive sufficient nutrients during the critical early growth phases, leading to suboptimal development that late-stage fertilization cannot rectify.

In conclusion, the findings indicate that optimal cabbage yields are best achieved by incorporating fertilization during the seedling stage and continuing through multiple growth stages (Fortune et al. 2010). This regime ensures that essential nutrients are supplied from the onset of growth, fostering robust development and enhancing yields. Effective management of the timing and combination of fertilization significantly improves crop productivity (Du et al. 2022).

Optimal fertilization regimes

The F210T1010 treatment is distinguished by its balanced approach, effectively integrating economic viability, environmental sustainability, and agronomic efficiency. Economically, limiting the regimen to just two fertilization events substantially cuts labor costs and operational expenses, a significant advantage over more frequently fertilized treatments. Although the nitrogen application rate is on the higher end, it strikes an economically viable balance by delivering high yields without excessive fertilizer costs. From an environmental perspective, fewer fertilization events help minimize disturbances to soil and water resources, thereby reducing the risk of environmental pollution (Everaarts and Booi 2000). Moreover, the moderate nitrogen application reduces the likelihood of nitrogen leaching and soil salinization, contributing to sustainable agricultural practices (Zhang et al. 2011). Agronomically, the timing of nutrient application at the seedling and maturity stages ensures that plants receive essential nutrients during crucial growth phases (Chuan et al. 2019). This optimizes nutrient uptake and utilization, fostering robust plant growth, high yields, and enhanced protein content. The high harvest index further indicates an efficient allocation of biomass to economically important plant parts, underscoring the treatment's overall effectiveness.

Table 4. Optimal fertilization management treatments for cabbage growth based on CROPGRO model simulations.

Treatment	Fertilizer amount (kg·hm^{-2})	Fertilization frequency	Fertilization stages	Head weight (kg·hm^{-2})	Head protein content (%)	Harvest index (%)
F210T1010	210	2	1010	4826	19.84	60.29
F210T1001	210	2	1001	4806	19.81	60.20
F210T1101	210	3	1101	4754	19.77	59.68
F210T1110	210	3	1110	4699	20.37	59.59
F220T1010	220	2	1010	4766	20.43	59.69
F220T1001	220	2	1001	4766	20.43	59.69
F220T1011	220	3	1011	4720	19.70	60.96
F220T1101	220	3	1101	4701	20.42	59.07
F230T1100	230	2	1100	4870	19.85	58.60
F230T1010	230	2	1010	4744	20.91	59.01
F230T1001	230	2	1001	4744	20.91	59.01
F230T1011	230	3	1011	4697	20.32	60.36
F240T1010	240	2	1010	4716	21.49	58.55
F240T1001	240	2	1001	4716	21.49	58.55

Conclusion

This study used the CROPGRO model to explore the impact of varied fertilization regimes on cabbage growth, yield, and quality, demonstrating significant effects. The model shows high accuracy in predicting key growth parameters under moderate to high nitrogen conditions; however, it requires refinement to address inaccuracies under severe stress scenarios effectively. Optimal nitrogen applications ranging from 180 to 220 kg·hm^{-2} are found to maximize head weight. In contrast, the peak protein content is achieved at 300 kg·hm^{-2}, and the most favorable harvest index is observed with nitrogen levels between 100 and 140 kg·hm^{-2}. Implementing a fertilization strategy with three to four events per season ensures continuous nutrient availability, supporting sustained growth. Specifically, applying fertilizers at the seedling and maturity stages significantly optimizes nutrient uptake and utilization. Among the various treatments evaluated, the F210T1010 regimen—characterized by two targeted fertilization events at critical growth stages—proves to be the most effective. This strategy not only yields high head weight and protein content but also reduces costs and minimizes environmental impacts, offering a balanced approach to enhancing cabbage production.

References Cited

Al-Solimani S. 2004. Effect of different rates of nitrogen and drip irrigation system on the yield of cabbage and some soil properties under arid conditions. Center of Scientific Publications. 15(1):95–111. https://doi.org/10.4197/met.15-1.9.

Ban HY, Sim D, Lee KJ, Kim J, Kim KS, Lee BW. 2015. Evaluating maize growth models “ceres-maize” and “ixim-maize” under elevated temperature conditions. J Crop Sci Biotechnol. 18(4):265–272. https://doi.org/10.1007/s12892-015-0071-3.

Boote KJ, Jones JW, Hoogenboom G, Pickering NB. 1998. The CROPGRO model for grain legumes, p 99–128. In: Tsuji GY, Hoogenboom G, Thornton PK (eds). Understanding options for agricultural production. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-3624-4_6.

Chuan L, Zheng H, Sun S, Wang A, Liu J, Zhao T, Zhao J. 2019. A sustainable way of fertilizer recommendation based on yield response and agronomic efficiency for chinese cabbage. Sustainability. 11(16):4368. https://doi.org/10.3390/su11164368.

Chun L, Chen FJ, Zhang FS. 2005. Root growth, nitrogen uptake and yield formation of hybrid maize with different N efficiency. J Plant Nutr Fert. 11(5):615–619. https://dx.doi.org/10.11674/zwyf.2005.0508.

Coolong T, Cassity-Duffey K, Da Silva ALBR. 2022. Influence of nitrogen rate, fertilizer type, and application method on cabbage yield and nutrient concentrations. HortTechnology. 32(2):134–139. https://doi.org/10.21273/HORTTECH04982-21.

Ding Y, Jiao X, Nie D, Li L, Huang M. 2012. Effects of combined application of different nitrogen sources and magnesium fertilizers on cabbage yield, quality and nutrient uptake. Chin J Eco-Agric. 20(8):996–1002. https://doi.org/10.3724/SP.J.1011.2012.00996.

Du Q-J, Xiao H-J, Li J-Q, Zhang J-X, Zhou L-Y, Wang J-Q. 2021. Effects of different fertilization rates on growth, yield, quality and partial factor productivity of tomato under non-pressure gravity irrigation. PLoS One. 16(3):e247578. https://doi.org/10.1371/journal.pone.0247578.

Everaarts AP, Booi R. 2000. The effect of nitrogen application on nitrogen utilization by white cabbage (*Brassica oleracea* var. Capitata) and on nitrogen in the soil at harvest. J Pomol Hortic Sci. 75(6):705–712. https://doi.org/10.1080/14620316.2000.11511311.

FAO. 2023. World Food and Agriculture – Statistical Yearbook 2023. Food and Agriculture Organization of the United Nations, Rome, Italy. https://doi.org/10.4060/cc8166en.

Fortune S, Hollies J, Stockdale EA. 2004. Effects of different potassium fertilizers suitable for use in organic farming systems on grass/clover yields and nutrient offtakes and interactions with nitrogen supply. Soil Use Manage. 20(4):403–409. https://doi.org/10.1111/j.1475-2743.2004.tb00389.x.

Gao Y, Duan J, Tian H. 2016. Expression of nitrogen transporter genes in roots of winter wheat (*Triticum aestivum* L.) in response to soil drought with contrasting nitrogen supplies. Crop Pasture Sci. 67(2):128–136. https://doi.org/10.1071/CP15152.

Goswami L, Ekblad A, Choudhury R, Bhattacharya SS. 2024. Vermi-converted tea industry coal ash efficiently substitutes chemical fertilization for growth and yield of cabbage (*Brassica oleracea* var. Capitata) in an alluvial soil: A field-based study on soil quality, nutrient translocation, and metal-risk remedia. Sci Total Environ. 907:168088. https://doi.org/10.1016/j.scitotenv.2023.168088.

Huimin F, Xiaorong F, Miller AJ, Guohua X. 2020. Plant nitrogen uptake and assimilation: Regulation of cellular pH homeostasis. J Exp Bot. 71(15):4380–4392. https://doi.org/10.1093/jxb/eraa150.

Jones JW, Hoogenboom G, Porter CH, Boote KJ, Batchelor WD, Hunt LA, Wilkens PW, Singh U, Gijsman AJ, Ritchie JT. 2003. The DSSAT cropping system model. Eur J Agron. 18(3–4):235–265. https://doi.org/10.1016/S1161-0301(02)00107-7.

Keating BA, Carberry PS, Hammer GL, Probert ME, Robertson MJ, Holzworth D, Huth NI, Hargreaves JNG, Meinke H, Hochman Z, McLean G, Verburg K, Snow V, Dimes JP, Silburn M, Wang E, Brown S, Bristow KL, Asseng S, Chapman S, McCown RL, Freebairn DM, Smith CJ. 2003. An overview of apsim, a model designed for farming systems simulation. Eur J Agron. 18(3–4):267–288. https://doi.org/10.1016/S1161-0301(02)00108-9.

Liang H, Gao S, Ma J, Zhang T, Wang T, Zhang S, Wu Z. 2021. Effect of nitrogen application rates on the nitrogen utilization, yield and quality of rice. Food Nutr Sci. 12:13–27. https://doi.org/10.4236/fns.2021.121002.

Mariotti M, Masoni A, Ercoli L, Arduini I. 2012. Optimizing forage yield of durum wheat/field bean intercropping through n fertilization and row ratio. Grass Forage Sci. 67(2):243–254. https://doi.org/10.1111/j.1365-2494.2011.00839.x.

Momesso L, Crusciol CAC, Leite MFA, Bossolani JW, Kuramae EE. 2022. Forage grasses steer soil nitrogen processes, microbial populations, and microbiome composition in a long-term tropical agriculture system. Agric Ecosyst Environ. 323:107688. https://doi.org/10.1016/j.agee.2021.107688.

Ozfidan-Konakci C, Alp FN, Arikan B, Balci M, Parmaksizoglu Z, Yildiztugay E, Cavusoglu H. 2022. The effects of fullerene on photosynthetic apparatus, chloroplast-encoded gene expression, and nitrogen assimilation in *Zea mays* under cobalt stress. Physiol Plant. 174(3):e13720. https://doi.org/10.1111/ppl.13720.

Qu ZM, Qi XC, Wang J, Chen Q, Li CL. 2019. Effects of nitrogen application rate and top-dressing times on yield and quality of chinese cabbage and soil nitrogen dynamics. Environ Pollutants Bioavailability. 31(1):1–8. https://doi.org/10.1080/09542299.2018.1546555.

Rongping W, Peiling L, Shuyi LI, Yucan Z, Xuwen D, Xingfu GU, Xinrong L. 2007. Effects of different nitrogen fertilizers and fertilization patterns on yield and quality of brassica chinensis. Ecol Environ. 03:1040–1043. https://doi.org/10.16258/j.cnki.1674-5906.2007.03.065.

Sharpley AN, Williams JR. 1990. Epic-erosion/productivity impact calculator: 1. Model determination. US Department of Agriculture Technical Bulletin No. 1768, US Government Printing Office, Washington DC.

Staugaitis G, Vi Kelis P, Rimantas Venskutonis P. 2008. Optimization of application of nitrogen fertilizers to increase the yield and improve the quality of chinese cabbage heads. Acta Agric Scand Sect B Soil Plant Sci. 58(2):176–181. https://doi.org/10.1080/09064710701467118.

Sun G, Hu T, Liu X, Peng Y, Leng X, Li Y, Yang Q. 2022. Optimizing irrigation and fertilization at various growth stages to improve mango yield, fruit quality and water-fertilizer use efficiency in xerothermic regions. Agric Water Manage. 260:107296. https://doi.org/10.1016/j.agwat.2021.107296.

Shundong D. 2012. Effects of density and application rates of nitrogen, phosphorus and potassium fertilizers on the yield and quality of mungbean. Soil Fert Sci China. 10:151–160. https://doi.org/10.11838/sfsc.1673-6257.23780.

Übelhör A, Munz S, Graeff-Hönninger S, Claupein W. 2015. Evaluation of the cropgro model for white cabbage production under temperate European climate conditions. Sci Hortic. 182:110–118. https://doi.org/10.1016/j.scienta.2014.11.019.

Yang B, Xiaoying LI, Wang Y, Chen M, Chen X. 2023. Effects of combined application of biochar-based organic fertilizer and reduced nitrogen fertilizer on soil enzyme activity and yield of purple cabbage (*Brassica oleracea* var. capita rubra) in Yuanmou County. Agric Biotechnol. 12(2):76–83.

Zhang F, Cui Z, Fan M, Zhang W, Chen X, Jiang R. 2011. Integrated soil–crop system management: Reducing environmental risk while increasing crop productivity and improving nutrient use efficiency in China. J Environ Qual. 40(4):1051–1057. https://doi.org/10.2134/jeq2010.0292.

Zhang H, Wang Q, Liu J, Hu F, Sun Z. 2012. Effect of different fertilization treatments on the yield of huang-huai region cabbage and nutrient use efficiency. J Henan Agric Univ. 46(4):392–396. https://doi.org/10.16445/j.cnki.1000-2340.2012.04.025.

Zhen-Ming N, Guo-Bin Z, Zhao-Fan L, Hao-Yu J, Ji-Hua Y. 2013. Effects of different nitrogen forms on nutrient uptake, yield formation and quality of cabbage. Acta Prataculturae Sinica. 22(6):68–76. https://doi.org/10.11686/cyxb20130609.