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Construction and Comparation of Critical Nitrogen Concentration Dilution Curves for Spring and Autumn Potato in China

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Abstract: Nitrogen is one of the essential nutrients for the growth and development of potato plants. The precise application of nitrogen can improve the yield and quality of potatoes and enhance their resistance to diseases. The changes in the critical N dilution curves of the shoot, root, and whole plants of potato were analyzed according to different N levels. The difference in the critical nitrogen concentration dilution curve of potatoes in spring and autumn was discussed. It is of great significance for the precise management of nitrogen fertilizer in spring and autumn potatoes. In this experiment, four field experiments were conducted using two potato cultivars (Zheshu956 and Yongma1) with four varying N application levels (N_0–N_3). Two identical varieties were planted at the same location in the spring and autumn and there was no significant difference in the selection of the same varieties between the two seasons. The dry matter and nitrogen concentration of roots, stems, leaves, and tubers were measured after transplantation at different stages. The results showed that the critical nitrogen concentration models for the shoot, root, and whole plant of potatoes were constructed as follows: spring potato shoot, N = 4.8712 $W^{-0.203}$, root, Nc = 1.8477 $W^{-0.157}$, and whole plant, Nc = 4.1679 $W^{-0.293}$; autumn potato shoot, Nc = 3.8653 $W^{-0.204}$, root, Nc = 2.1529 $W^{-0.158}$; and whole plant, Nc = 3.2569 $W^{-0.304}$. The critical nitrogen curves for the aboveground part and the whole plant of spring potato were significantly higher than that of autumn potato. Under N_2 (160 kg ha^{-1}) treatment, both spring and autumn potatoes reach their maximum yield. The critical nitrogen concentration dilution curve based on the whole plant was determined to be more appropriate for potatoes. The critical nitrogen concentration curves of potatoes in spring and autumn were significantly different for the aboveground part and the whole plant, but there was no significant difference for the underground part. The separately constructed nitrogen nutrition indices can be used to diagnose the nitrogen requirements of spring and autumn potatoes.

Keywords: spring potato; autumn potato; critical nitrogen concentration; nitrogen nutrition index; model construction

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1. Introduction

Potatoes belong to the Solanaceae family. In the growth of potatoes, nitrogen fertilizer plays a crucial role. Nitrogen is a component of proteins, nucleic acids, different active enzymes, chlorophyll, and other substances [1]. As a result, the amount of nitrogen in plants can be utilized to gauge their physiological, biochemical, and growth and development stages [2–4], as well as to indirectly impact the yield and quality [5–7].

Different potato plant organs, including the roots, stems, leaves, and tubers, require a moderate nitrogen supply at different growth stages in order to sustain normal growth and metabolic activity. Plants require a lot of nitrogen during the tuber formation and expansion processes. Nitrogen deficiency will reduce potato size and the number of tubers, resulting in yield reduction. The appropriate application of nitrogen fertilizer could improve quality and increase resistance to diseases of potatoes. Excessive nitrogen fertilizer can lead to the excessive growth of stems and leaves, which in turn can impede tuber formation. Unlike cereal crops, such as wheat [8], rice [9], and so on, the main harvesting organs of potatoes are located underground. In terms of nitrogen need, the crop growth and development and yield formation of potatoes are significantly different from cereal crops. The critical nitrogen concentration curve based on the aboveground part is mainly constructed for cereal crops, while the critical nitrogen concentration curve based on the whole plant is more suitable for potato [10].

The critical nitrogen concentration is the minimum nitrogen concentration required for a crop to reach maximum dry matter, and the critical nitrogen concentration dilution curves constructed can be used to diagnose crop nitrogen requirements [11,12]. Its dilution curve model is $Nc = a*W^{-b}$, where W is the maximum dry matter, Nc is the critical nitrogen concentration, and a and b are parameters. In recent years, many scholars have constructed potato critical nitrogen dilution curve models. The models established in different regions or different varieties are not the same [13–15]. Giletto et al. (2015) [16] pointed out that the nitrogen concentration of potatoes is affected by varieties, and the length of the variety growth period will affect the nitrogen concentration of potatoes. Bohman et al. (2023) [17] proposed that the critical nitrogen dilution curve of potatoes is affected by a G*E*M interaction effect. That is, the parameter value of the curve is jointly controlled by genes, environment, and management measures. Giletto et al. (2020) [14] constructed the critical nitrogen concentration of potatoes in Argentina and Canada and found that the critical nitrogen concentration curves aboveground were significantly different, which may be caused by the climate differences between the two regions. Bélanger et al. (2001) [12] showed that irrigation level has a significant impact on potato nitrogen concentration. Li et al. (2016) [18] researched that when water is lacking, potatoes meet difficulty in absorbing nitrogen, resulting in lower nitrogen levels. The organs that synthesize assimilates are "sources", while the organs that accumulate assimilates are referred to as "sinks." The yield is increased by adjusting the ratio between the source and the sink. Water also affects the activity of nitrogen-absorption-related enzymes, thereby affecting nitrogen absorption.

Many scholars have also pointed out the influence of environmental factors on the curve in other crops, such as wheat [8], rice [9,19], and so on. Temperature affects the growth and development rate of crops and has a significant effect on the critical nitrogen concentration [8,9]. He et al. (2017) [19] constructed a curve for the critical nitrogen concentration of two-season rice in the southern region of China and showed that the differences in the curve were caused by the differences in climatic conditions between early rice and late rice. According to Zhao et al. (2022) [20], the critical nitrogen concentration dilution curve based on winter wheat was changed during the water deficit. Guo et al. (2020) [21] created a series of humidity concentration gradients and found that the critical nitrogen concentration curve varied with the humidity of the wheat-developing environment. Wang et al. (2018) [22] suggested that crop planting density affects the critical nitrogen concentration curve constructed from rye.

Potatoes are cool-loving crops. In northern China, potatoes are widely planted in spring. As the temperature drops in autumn, some areas can also plant potatoes for a season. The planting area of autumn potatoes is increasing year by year. However, the climatic conditions in spring and autumn are quite different for potatoes. Under the same variety, it is not clear whether the critical nitrogen concentration curve constructed for spring potatoes can be used to diagnose the nitrogen nutritional status of autumn potatoes. Further exploration is needed to determine which organ's critical nitrogen concentration curve is more stable for nutritional diagnosis in spring and autumn. In recent years, many scholars have constructed critical nitrogen concentration curves for crops, such as rice [9,19], wheat [8,21], rye [22], and so on. However, a widely used model for potatoes needs to be constructed.

Therefore, the main objectives of this study were (1) to explore the construction of critical nitrogen concentration curves for potato stems, roots, and whole plants in spring and autumn and to explore the differences between the critical nitrogen curves of the potatoes in spring and autumn; (2) to construct a nitrogen nutrition index (NNI) model to diagnose the nitrogen nutritional status of potatoes in spring and autumn; and (3) to clarify which organs have critical nitrogen concentration curves that are more stable for nutrition diagnosis in spring and autumn, so as to realize nitrogen nutrition diagnosis for potatoes in spring and autumn.

2. Materials and Methods

2.1. Experimental Design

Four field experiments were carried out in Zhejiang Province, China, in 2022 and 2023 (Lin'an: (30°15′ N, 119°43′ E)), among which the amount of P and K applied were kept consistent. Four nitrogen concentration gradients of N_0 (0 kg ha^{-1}), N_1 (80 kg ha^{-1}), N_2 (160 kg ha^{-1}), and N_3 (240 kg ha^{-1}), and two varieties (Zheshu956 and Yongma1) were selected for the experiments. The planting and sampling dates for each experiment are shown in Table 1. Zheshu956 and Yongma1 were planted in the spring and autumn of 2022 as experimental comparisons, and in the spring and autumn of 2023 as model verification. The plots were arranged in a split-plot design with three replicates. In order to simulate the difference in temperature between spring and autumn and to control the same amount of irrigation, all four experiments were conducted in a dry shed with a simulated rainfall system above the shed. During the planting period, the indoor and outdoor temperatures were consistent, and the field water holding capacity was maintained at around 60–70% in the four experiments. The maximum and minimum temperature and the hours of sunshine on that day were recorded each day. The experimental areas were planted at a density of 60,000 plants ha^{-1} in plots of the same size, with row spacing of 60 plants and planting spacing of 25 cm.

Table 1. Fertilizer design and sampling date of field trials.

Experiment	Site	Cultivar	N Rate (kg ha^{-1})	N and K Rate (kg ha^{-1})	Planting Date	Sampling Date (Days After Planting)
Spring potato (2022)	Lin'an (30°15′ N, 119°43′ E)	Yongma1, Zheshu956	N0 (0), N1 (80), N2 (160), N3 (240)	P (100), K (80)	2-Mar	29, 43, 55, 69, 76
Autumn potato (2022)		Yongma1, Zheshu956	N0 (0), N1 (80), N2 (160), N3 (240)	P (100), K (80)	6-Sep	36, 49, 51, 58, 68
Spring potato (2023)		Zheshu956	N0 (0), N1 (80), N2 (160), N3 (240)	P (100), K (80)	19-Mar	39, 53, 67, 79
Autumn potato (2023)		Zheshu956	N0 (0), N1 (80), N2 (160), N3 (240)	P (100), K (80)	14-Sep	30, 44, 58, 70

Table 2 lists the total N, available K, and available P in the soil of the four tests. The Walkley–Black titration method was used to randomly collect surface soil samples (0–0.20 m depth) from the experimental site.

The trend of the average values of the highest and lowest temperatures per week after March 2nd (2022 spring potato), September 6th (2022 autumn potato), March 19th (2023 spring potato), and September 14th (2023 autumn potato) are shown in (Figure 1).

Figures 1 and 2 show the changes in temperature and sunshine hours during the potato growth period in spring and autumn. In the experiment, during the spring potato cultivation season, the highest temperature range was 15–25 °C, and the lowest temperature range was 5–15 °C. On the other hand, during the autumn potato cultivation season, the highest temperature range was 10–20 °C, and the lowest temperature range was −5–10 °C. The average monthly temperatures from March to June during spring potato cultivation in 2022 were 14 °C, 17 °C, 20 °C, and 25 °C; The average temperatures from September to December during the autumn potato cultivation season in 2022 were 24 °C, 18 °C, 10 °C, and 5 °C. The accumulated temperature was 1861.5 °C in spring and 1187.5 °C in autumn. The total sunshine duration was 458.05 h in spring and 373.61 h in autumn.

Table 2. Soil properties at the experimental sites.

Experiment	Soil Type	Total N (g kg^{-1})	Available P (mg kg^{-1})	Available K (mg kg^{-1})
Spring potato (2022)	Clay loam	1.23	65.8	144.2
Autumn potato (2022)		1.27	69.4	142.6
Spring potato (2023)		1.31	66.5	143.8
Autumn potato (2023)		1.25	66.9	140.7

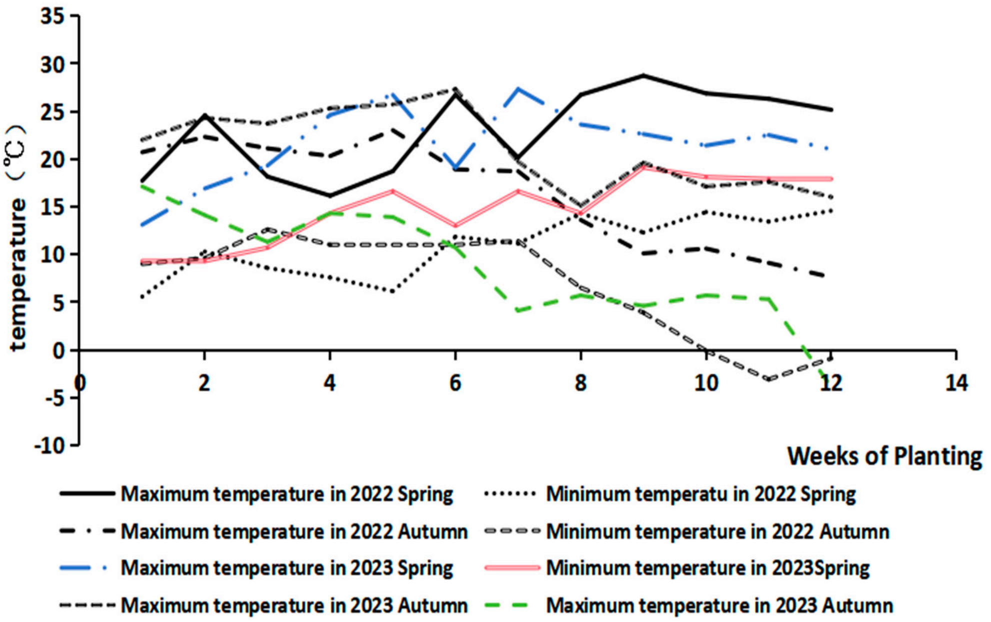


Figure 1. Environmental temperature changes after planting.

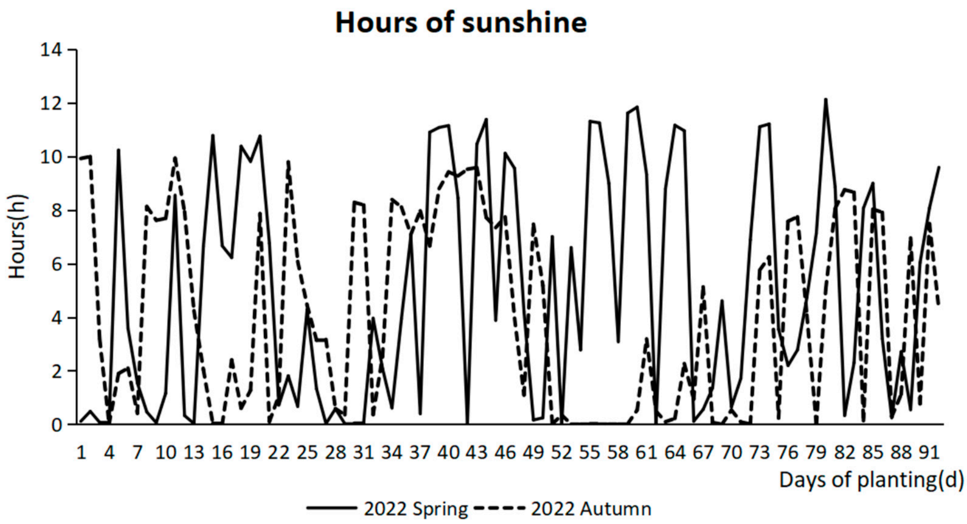


Figure 2. Hours of sunshine changes after planting.

2.2. Sampling and Measurement

Potato samples were taken every 15–20 days after excavation in 2022 for a total of five samples. Samples were taken every 15–20 days after the potato was unearthed in 2023, for a total of four samples. From each plot, three plants exhibiting consistent and steady growth were chosen at random and divided into leaves, stems, roots, and tubers at the seedling stage, tuber formation stage, tuber swelling stage, starch accumulation stage, and tuber dormancy stage. The entire potato root was dug out and separated into fiber and storage roots. The samples were oven-dried to a consistent weight for 30 min at 100 °C and 48 h at 80 °C (Shanghai Jinghong Experimental Equipment Co., Ltd., Shanghai, China). A medium-sized pulverizer (Hangzhou Daji photoelectric instrument Co., Ltd., Hangzhou, China) was used to grind the separated organs after the dry matter of each organ was weighed. The samples' total N was then ascertained using a Kjeldahl N analyzer (Shandong Haineng Scientific Instrument Co., Ltd., Weifang, China) [23].

2.3. Model Construction

The nitrogen concentration is frequently used to determine how much nitrogen they need and to assess how nutrient-rich they are [24]. However, other researchers' essential nitrogen concentration curves [25,26] were mostly based on cereal crops, while potatoes are underground crops, and their underground organs are what we eventually harvest. Consequently, we must create a model of the potato's critical nitrogen content dilution curve. Curves of the critical shoot N, root N, and the whole plant's N concentration were constructed, following the ways proposed by Greenwood et al. (1990) [27]. Lemaire et al. (1984) [28] proposed the concept of critical N concentration in plant dry matter, which means the minimum concentration of nutrients needed by the crop to reach maximum growth rates at a given rate of biomass accumulation:

$$N_c = a \times W^{-b} \quad (1)$$

W is the maximum dry matter, Nc is the critical nitrogen concentration, and a and b are parameters. The traditional method was used to construct the critical nitrogen concentration dilution curve, and the specific steps were as follows:

(1) Each sampling point was divided into N-limited treatment and non-N-limited treatment; (2) the relationship between the N-limited treatment group and nitrogen concentration was fitted with an oblique line; (3) the mean value of plant dry matter in the non-N-limited treatment group at each sampling date was represented by a vertical line; (4) there is an intersection point between the oblique line and the vertical line whose coordinate is the critical N concentration point of each sampling date.

In addition to the aboveground and underground parts, the critical nitrogen concentration curve based on the whole potato plant was constructed, and the calculation formula of the whole-plant biomass of potato was as follows: $DM_w = DM_a + DM_u$. In the formula, DM_a is shoot dry weight, DM_u is root dry weight, and DM_w is the whole-plant dry weight. Whole-plant nitrogen concentration of potato: $N_w = (DM_a{*}N_a + DM_u{*}N_u)/DM_w$, where N_w is the whole-plant nitrogen concentration, DM_a is shoot dry weight, DM_u is root dry weight, N_a is the shoot nitrogen concentration, N_u is the root nitrogen concentration, and DM_w is the whole-plant dry weight.

The nitrogen nutrition index value (NNI) can be used to determine the state of nitrogen nutrition. It is a quantitative indicator of the nitrogen sufficiency or deficiency in plants. The expression of NNI was as follows:

$$NNI = N_a/N_c \quad (2)$$

where N_a is the actual measured nitrogen value and N_c is the nitrogen value obtained according to the N_c dilution model [29]. When NNI = 1, plant N status is considered optimal. NNI > 1 indicates that there is excessive N in the plant, and NNI < 1 indicates N deficiency and that we need to supply the nitrogen element. NNI can be used to forecast yield in addition to nutritional status [30,31].

2.4. Data Analysis

Microsoft Excel 2010 and SPSS (version 20.0) were used to analyze the variance of the experimental data. The differences in shoot dry matter, root dry matter, whole-plant dry matter, shoot N concentration, root N concentration, and whole-plant N concentration under different N treatments were assessed using the least significant difference (LSD) test ($p < 0.05$). One-way ANOVA (F test) was used to analyze the changes in critical N concentration dilution curves of the shoots, roots, and whole plants under different varieties and N treatments. The significance level was $p < 0.05$ for all tests.

3. Results and Analysis

3.1. Changes in Dry Matter of Potatoes Under Different Nitrogen Levels

3.1.1. Changes in Shoot Dry Matter Weight with Growth Period

The shoot dry matter of Zheshu956 and Yongma1 increased continually during the whole growth period. There were no significant differences among the four nitrogen levels at the sprouting and seedling stages. The increase rate for shoot dry matter slows down during the tuber formation and enlargement periods. This is because the growth center of the potato has moved from the shoot to the root, photosynthetic products are being supplied to the underground, and the growth rate of stems and leaves is slowing down. There was a trend of increases in the shoot dry matter of Zheshu956 and Yongma1 with the increase in nitrogen application rates (Figure 3).

3.1.2. Changes in Root Dry Matter Weight with Growth Period

The root dry matter of both Zheshu956 and Yongma1 increased continually during the whole growth period. There were no significant differences among the four nitrogen levels at the sprouting and seedling stages. After 50 days of planting, the potato yield increased significantly due to the expansion of tubers. In the last stages, the root dry matter of Zheshu956 and Yongma1 both reached the maximum. With increasing nitrogen application, the potato root dry weight exhibited a trend of initially increasing and then decreasing. Compared to other treatments, the potato root dry matter was the highest in the N_2 treatment, while shoot dry matter was the highest in the N_3 treatment.

3.2. Changes in Nitrogen Concentration of Potato Plants Under Different Nitrogen Levels

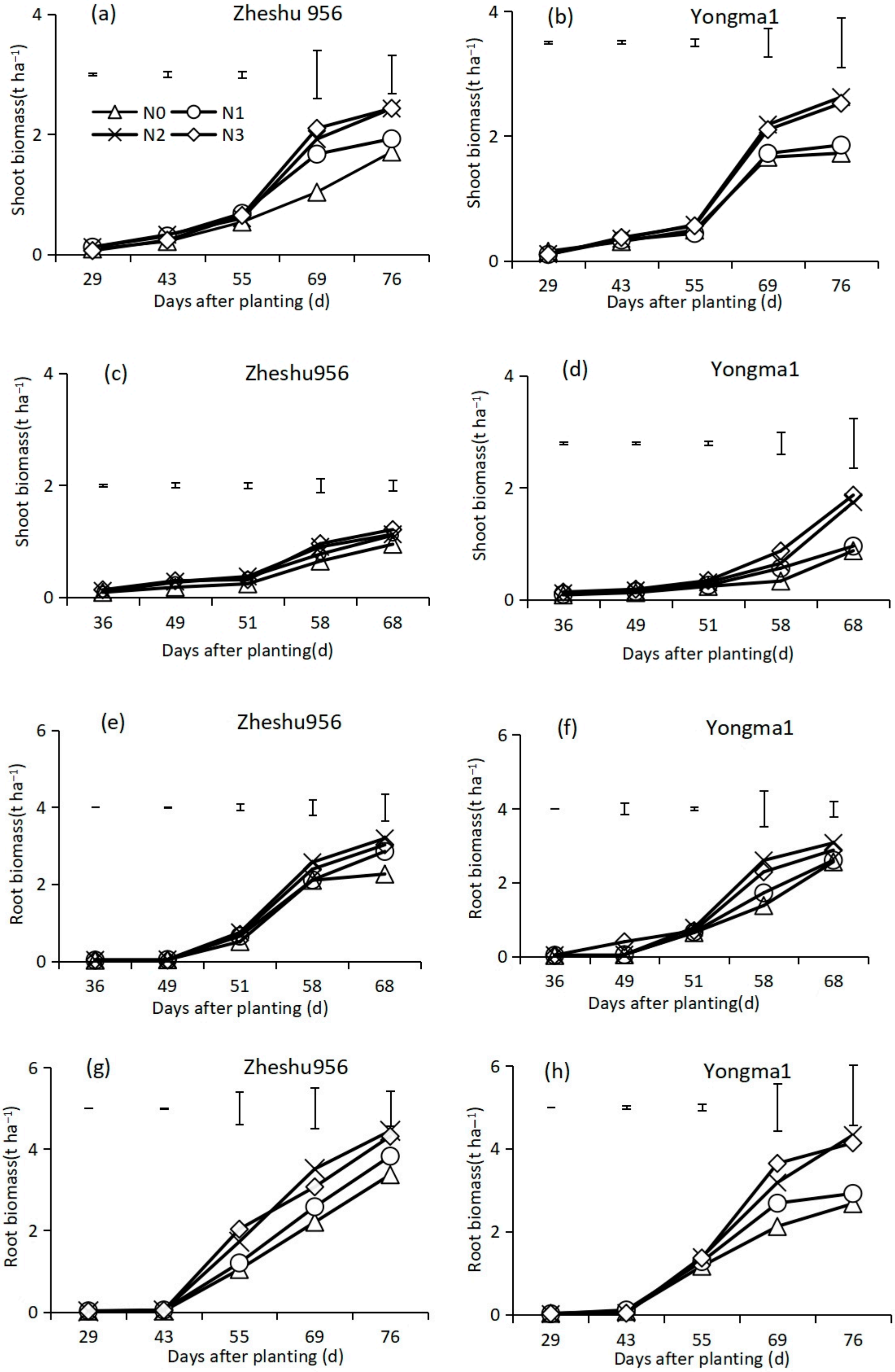
3.2.1. Changes in Shoot Nitrogen Concentration

The shoot nitrogen content of Zheshu956 and Yongma1 showed a decreasing trend as the potato plants grew. As shoot biomass increases, the nitrogen concentration is diluted and the shoot nitrogen concentration decreases continually.

The change ranges of the shoot nitrogen concentration for spring and autumn potatoes of the Zheshu956 variety were 2.66–6.96% and 1.36–6.65%, respectively. The change ranges of shoot nitrogen concentration for spring and autumn potatoes of the Yongma1 variety were 2.95–6.59% and 1.01–6.37%, respectively (Figure 4).

3.2.2. Changes in Root Nitrogen Concentration

Figure 4 illustrates how the nitrogen concentration values of the root plants of Zheshu956 and Yongma1 steadily drop as the potato plants grow, even at the same nitrogen application level. As plant biomass increases, the nitrogen concentration is diluted and the plants' nitrogen concentration decreases. The N concentrations in the roots of Zheshu956 spring and autumn potatoes were 0.94–4.07% and 0.38–4.02%, and in the Yongma1 potatoes, they were 0.79–4.69% and 1.40–4.13%.



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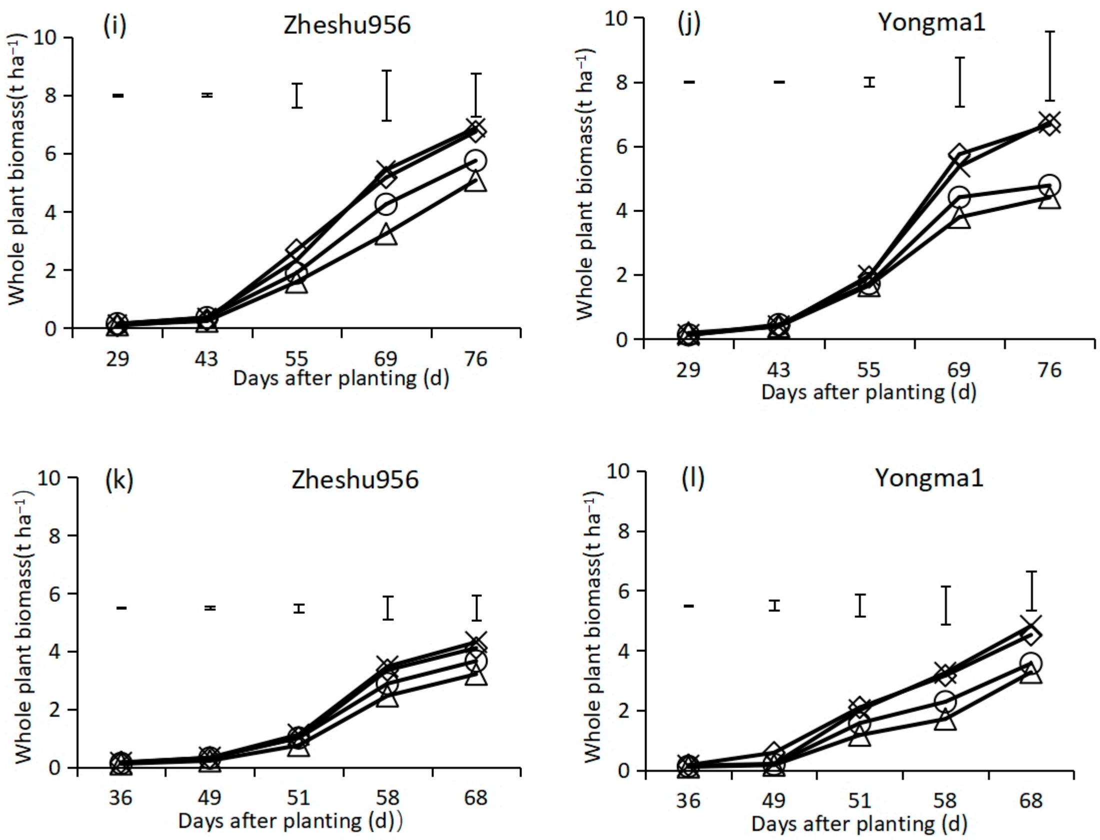


Figure 3. Changes in potato shoot dry matter (t ha^{-1}) of Zheshu956 (**a**) and Yongma1 (**b**) in spring 2022 and Zheshu956 (**c**) and Yongma1 (**d**) in autumn 2022; changes in potato root dry matter (t ha^{-1}) of Zheshu956 (**e**) and Yongma1 (**f**) in spring 2022 and Zheshu956 (**g**) and Yongma1 (**h**) in autumn 2022; changes in potato whole-plant matter (t ha^{-1}) of Zheshu956 (**i**) and Yongma1 (**j**) in spring 2022 and Zheshu956 (**k**) and Yongma1 (**l**) in autumn 2022. Vertical lines represent the LSD values ($p < 0.05$) at each sampling date.

3.2.3. Changes in Whole Nitrogen Concentration

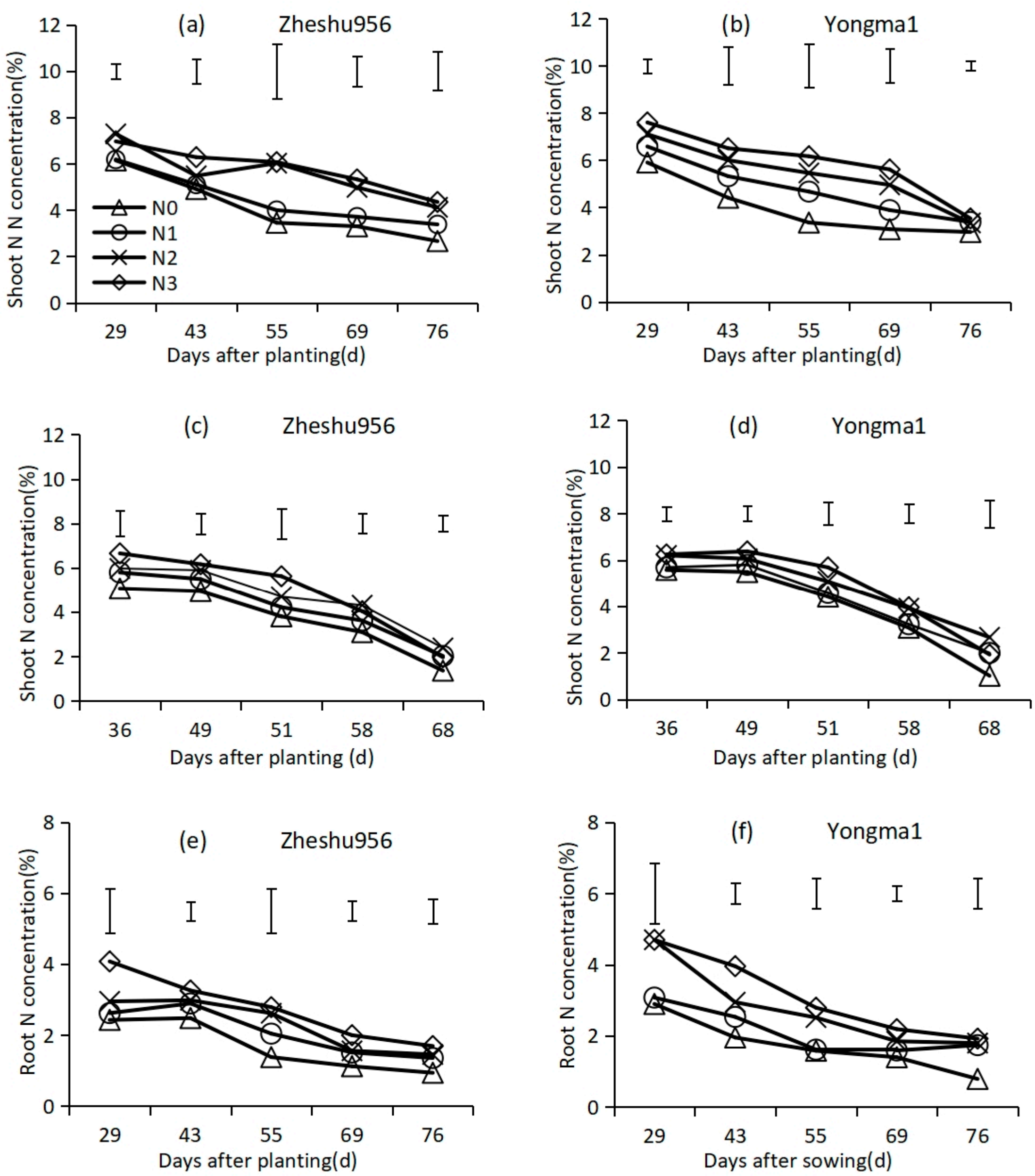
Figure 4 illustrates that the two potato varieties showed a decreasing trend with the increase in planting days, which was consistent with the phenomenon of nitrogen dilution in crops. However, the nitrogen concentration of different nitrogen application treatments was also different, and it increased first and then decreased with the increase in nitrogen application. Zheshu956 spring and autumn potato total changes were 1.64–6.82% and 1.09–6.18%, respectively. The variation in the Yongma1 ranges was 1.53–5.88% and 1.66–7.06%.

3.3. Data Analysis of Critical Nitrogen Concentration Dilution Curve for Potatoes

The critical N concentration curve for the shoot, root, and whole plant was constructed based on dry matter and nitrogen concentration (Figure 5). There are no significant differences between Zheshu956 and Yongma1 in the critical nitrogen concentration curves of the shoot, root, and whole plant. Therefore, the critical N curves of two cultivars can be merged into a single curve. Autumn potatoes have a lower nitrogen content than spring potatoes, and the biomass of autumn potatoes was also lower than that of spring potatoes. There are significant differences in critical shoot and whole-plant nitrogen curves between spring and autumn potatoes, while there are no significant differences in the critical root nitrogen concentration curves of spring and autumn potatoes. Temperature has a greater impact on the critical nitrogen concentration of the aboveground, while its impact on the critical nitrogen concentration of the underground is smaller. The model was created by fitting the dry matter with its corresponding nitrogen concentration as a function. Figure 5 shows that the root nitrogen concentration of both spring and autumn potatoes exhibits a gradual decline as the biomass increases ($p < 0.05$). The specific parameters for the model are shown in Table 3.

Table 3. The parameter values of the critical N dilution curve of the shoot, root, and whole plant.

Date	A Value	B Value	R^2
The shoot curve of spring potato	4.8712	−0.203	0.779
The shoot curve of autumn potato	3.8653	−0.204	0.816
The root curve of spring potato	1.8477	−0.157	0.8996
The root curve of autumn potato	2.1529	−0.158	0.9123
The whole curve of spring potato	4.1679	−0.293	0.9335
The whole curve of autumn potato	3.2569	−0.304	0.9068



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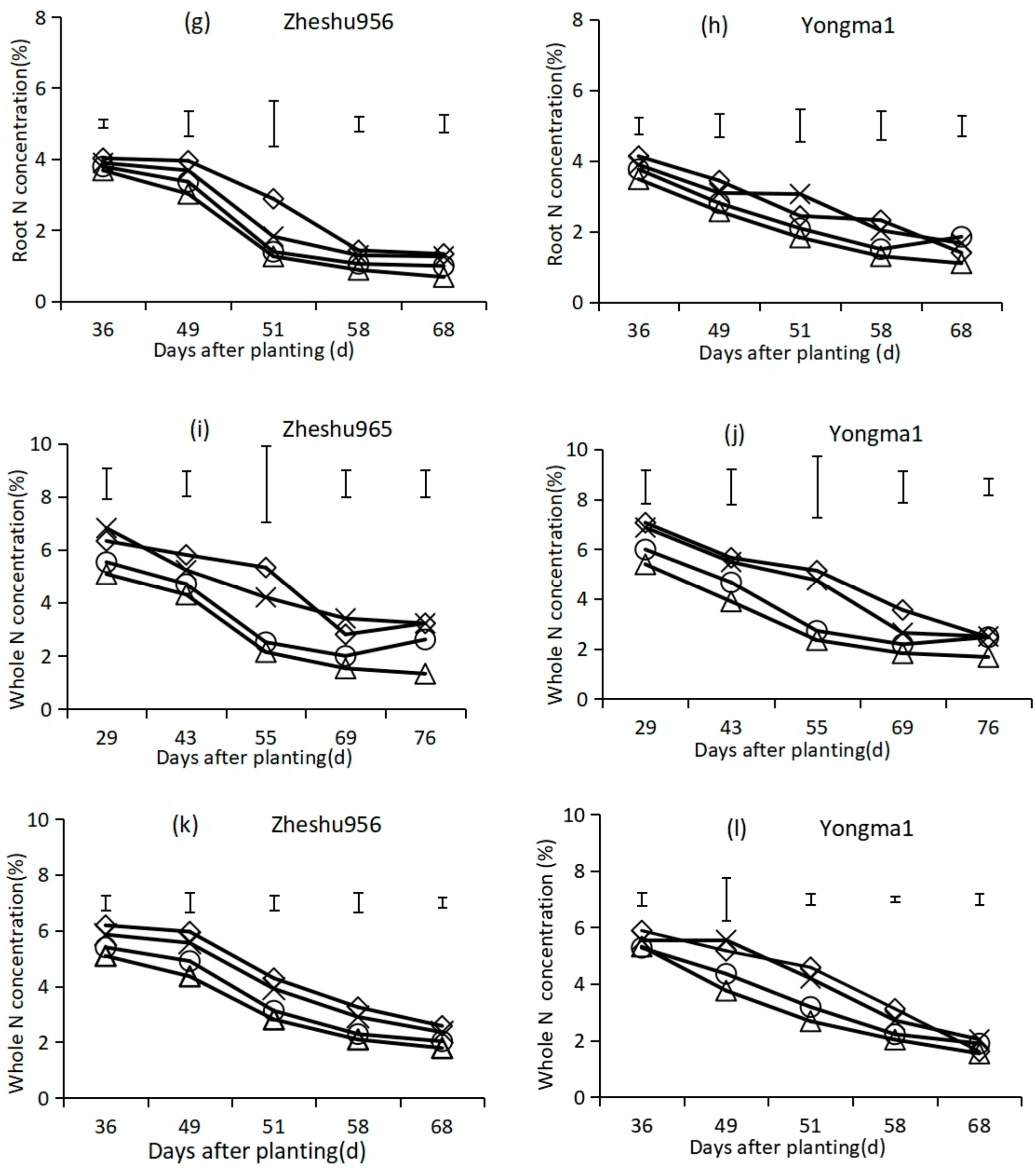

Figure 4. Changes in shoot nitrogen concentration of Zheshu956 (**a**) and Yongma1 (**b**) in spring 2022 and Zheshu956 (**c**) and Yongma1 (**d**) in autumn 2022; changes in root nitrogen concentration of Zheshu956 (**e**) and Yongma1 (**f**) in spring 2022 and Zheshu956 (**g**) and Yongma1 (**h**) in autumn 2022; changes in the whole-plant nitrogen concentration of Zheshu956 (**i**) and Yongma1 (**j**) in spring 2022 and Zheshu956 (**k**) and Yongma1 (**l**) in autumn 2022. Vertical lines represent the LSD values ($p < 0.05$) at each sampling date.

3.4. Validation of the Critical N Concentration Dilution Curve

The shoot, root, and whole-plant critical nitrogen dilution curves of spring and autumn potatoes were verified by independent data. The verified data points are divided into N-limited and non-N-limited groups. From Figure 6, it can be seen that almost all data points limited by N are located below the curve, while data points not limited by N are located above the curve. Under N_2 level conditions, Zheshu956 and Yongma1 are closest to the critical nitrogen concentration dilution curve of spring and autumn potatoes.

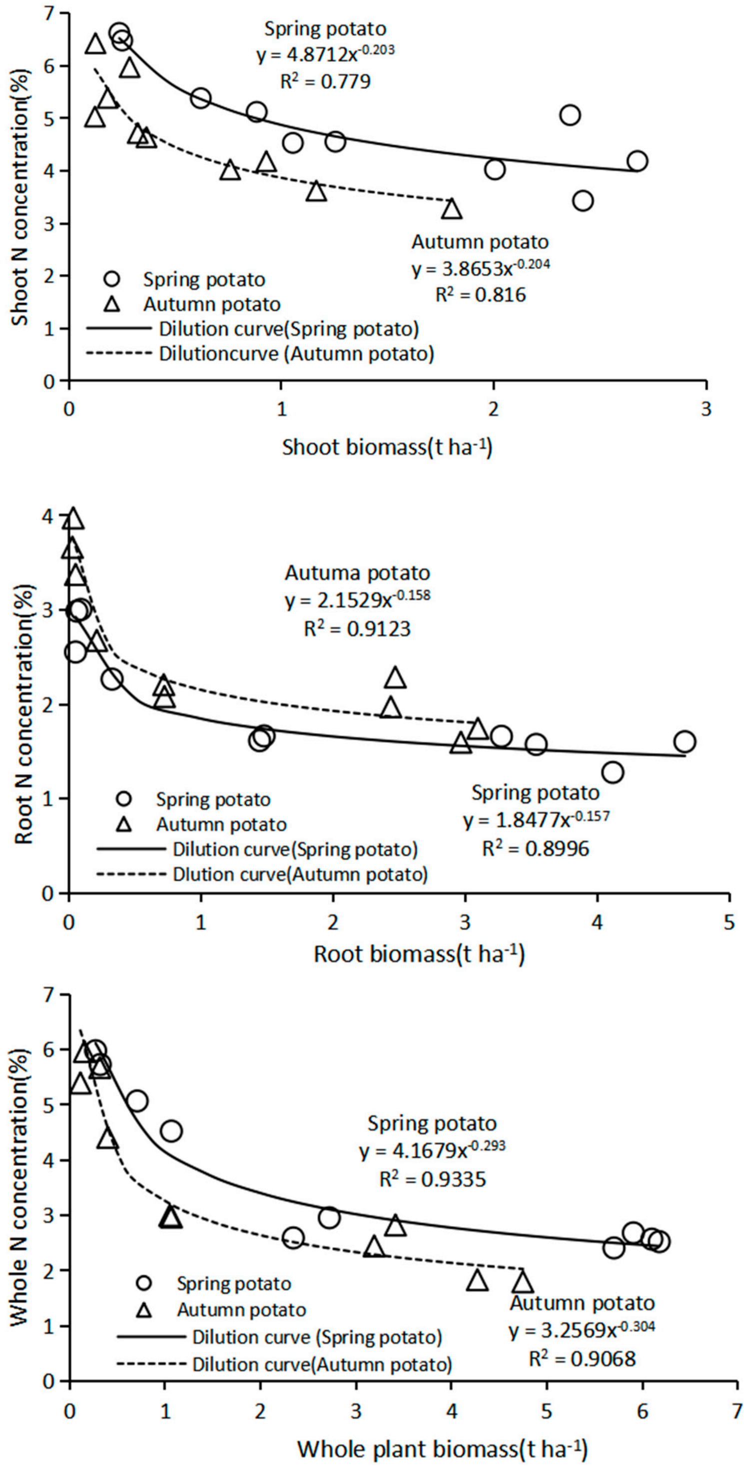

Figure 5. Dilution curve of critical nitrogen concentration in the shoot, root, and whole plant.

3.5. Data Analysis of Potato Nitrogen Nutrition Index

The nutritional index obtained from the experiments is shown in Figure 7. Figure 7 shows that the NNI of the shoot part of Zheshu956 varied between 0.56 and 1.20, while the variation range of the shoot part of Yongma1 was 0.67 to 1.54. Overall, with the increase in nitrogen fertilizer levels, the NNI of the shoot parts of Zheshu956 and Yongma1 increased continuously during the whole growth period. The NNI value of the root part of Zheshu956 varied between 0.6 and 1.31, while the variation range of the root part of Yongma1 was 0.47 to 1.65. Overall, with the increase in nitrogen fertilizer levels, the NNI of the root parts of Zheshu956 and Yongma1 increased continuously during the whole growth period. The NNI value of Zheshu956 varied between 0.57 and 1.30, while the variation range of Yongma1 was 0.61 to 1.46. Overall, with the increase in nitrogen fertilizer levels, the NNI of Zheshu956 and Yongma1 continued to increase during the whole growth period.

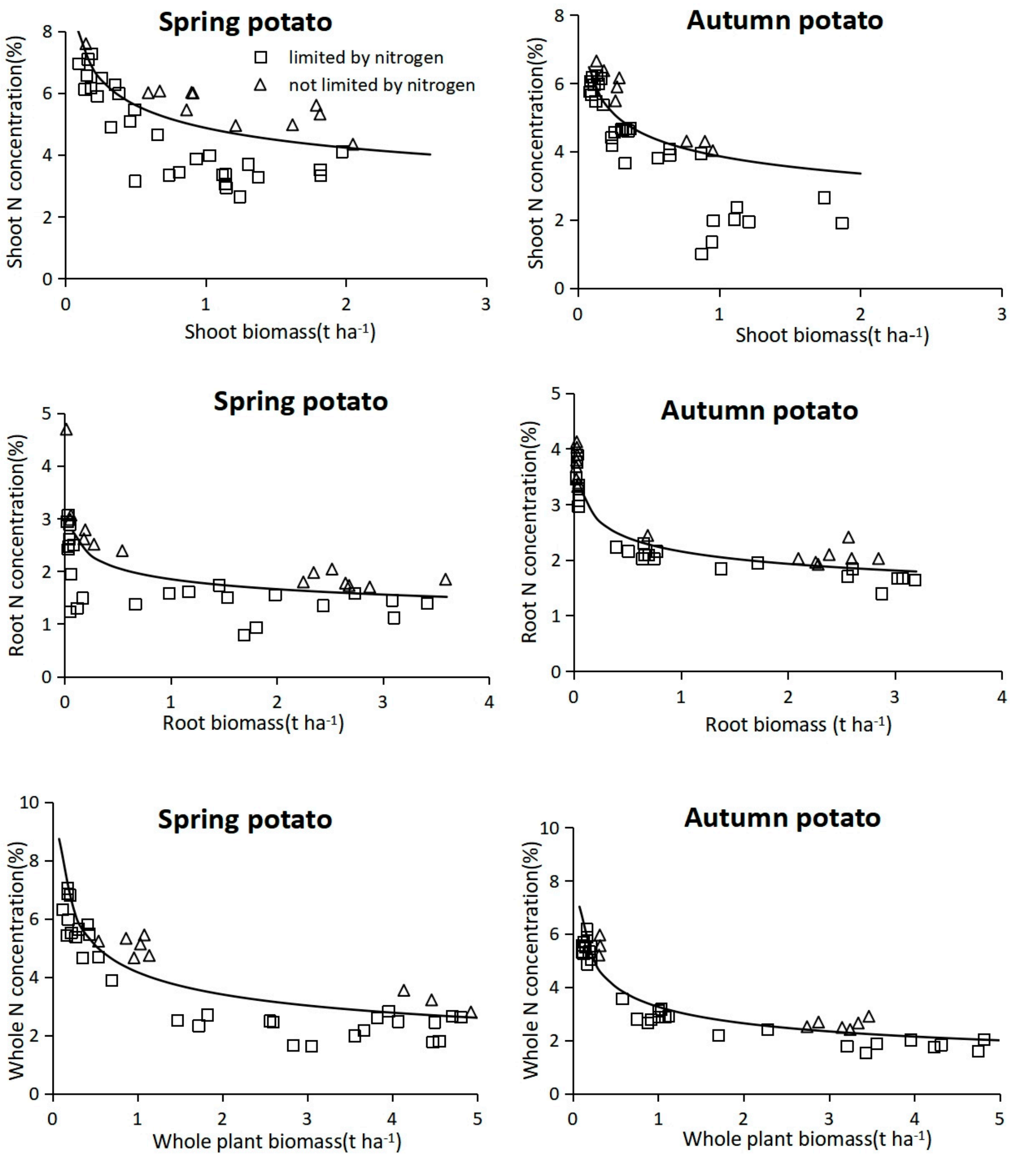

Figure 6. Comprehensive validation of Nc dilution curve using independent data from an experiment conducted.

The NNI of the shoot, root, and whole plant of Zheshu956 and Yongma1 potatoes was less than 1 for N_0 and N_1 treatments, which shows that potatoes with N_0 and N_1 treatments were in a deficit state. However, for the N_3 treatment, the NNI was often more than 1, which indicates the potatoes were in an excess state. On the other hand, the NNI of potatoes tended to approach 1 under N_2 treatment, which indicates that the potatoes were in an optimal state.

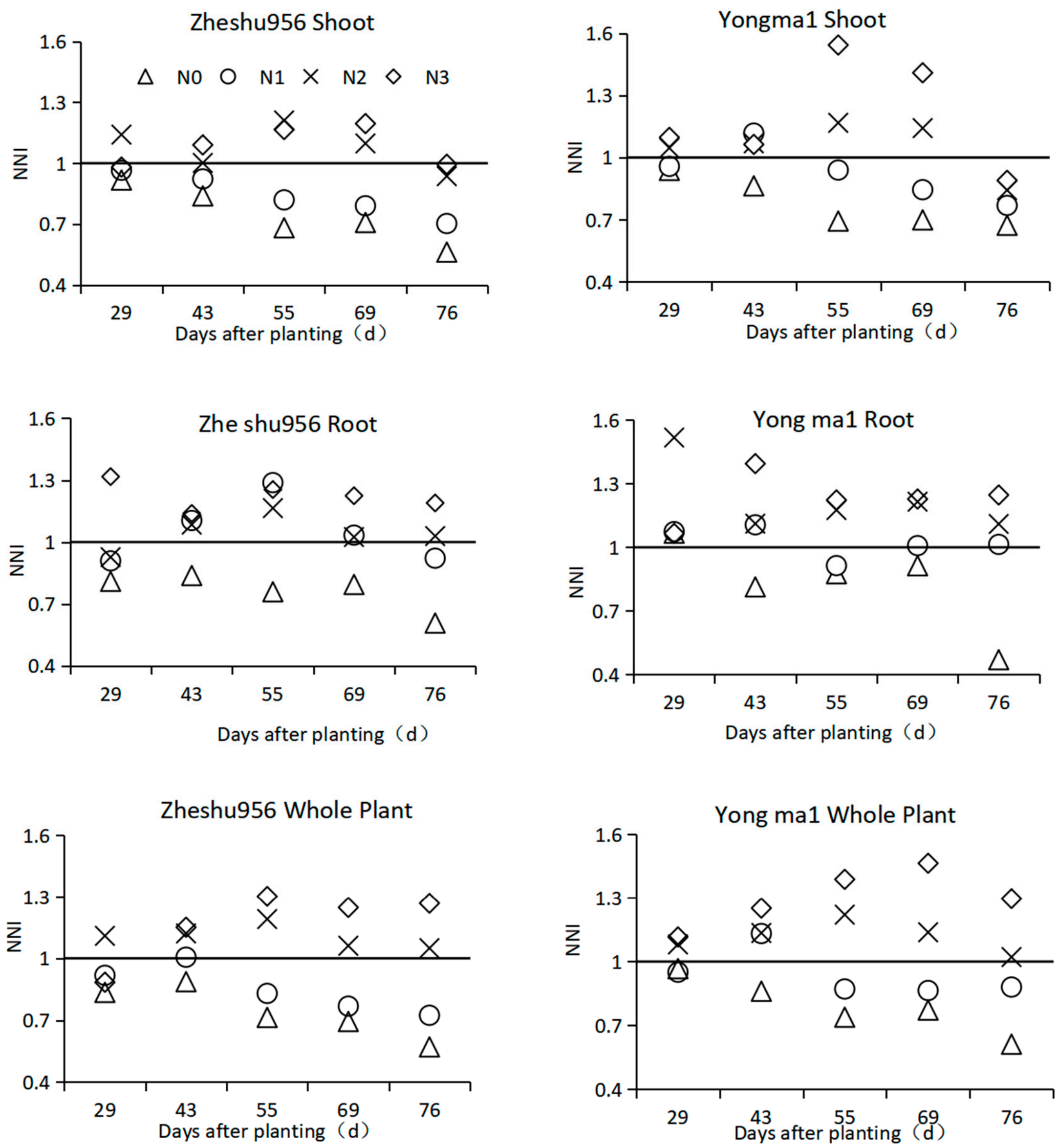

Figure 7. Effects of different N application rates on the nitrogen nutrition index (NNI) of shoots, roots, and whole plants of two varieties.

4. Discussion

4.1. Comparison with Critical Nitrogen Dilution Curves for Potato

Previous studies [32,33] have demonstrated that the critical nitrogen concentration dilution curve constructed based on the whole potato plant has higher accuracy compared to those constructed for aboveground shoots or roots alone. Based on this insight, our experiment employed the whole-plant dry matter in conjunction with its corresponding nitrogen concentration to construct a critical nitrogen concentration dilution curve model for the whole growth period of potatoes. Figure 8 shows the critical nitrogen concentration dilution curves constructed based on the whole potato plant by other scholars [13,14,34]. The critical nitrogen concentration curve for spring and autumn potatoes was constructed based on this experiment. a and b are parameters of the critical N concentration mode [35]. Parameter a represents the critical nitrogen concentration when plant dry matter is 1 t ha^{-1}, and parameter b is a statistical parameter determining the slope of the curve [32,36,37]. Parameters a and b are related to factors such as crop variety, soil fertility, climate, water content, and temperature. Du et al. (2020) [38] reported that the degree of soil fertility is correlated with the values of parameters a and b. Fertile soil can boost plants' ability to absorb nitrogen in comparison to infertile soil, which increases the values of parameters a and b. In addition to soil, parameters a and b are also related to the growth environment and climate of the plants. Prystupa et al. (2018) [39] created a critical nitrogen content dilution curve for barley in Argentina and highlighted how temperature and rainfall, two external variables, affected the curve. Temperature affects the nitrogen absorption of barley at the critical stage of grain number per spike formation and then affects the yield. In this experiment, the varieties and fertilization programs selected for spring and autumn potatoes were the same. The critical N dilution curve based on the whole plant of spring potato was closer to other curves, while the critical nitrogen concentration curve of autumn potato was significantly lower than other curves (Figure 8).

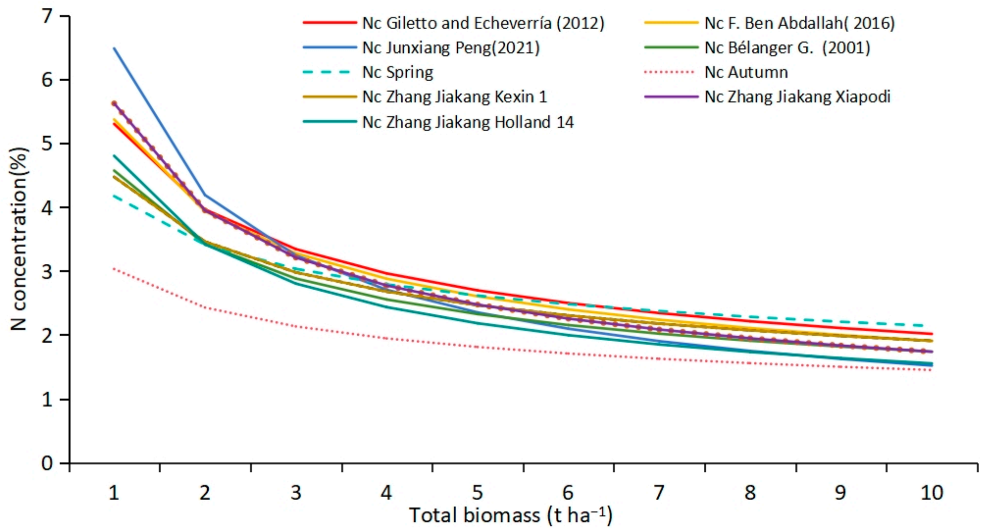

Figure 8. Comparison with critical nitrogen dilution curves for a potato crop (Bélanger G (2001) [12]; F. Ben Abdallah 2016 [13]; Giletto and Echeverría (2012) [16]; Zhang jiakang (2020) [33]; Junxiang Peng (2021) [34]).

4.2. Effect of Climate on the Critical Nitrogen Concentration Curve of Potatoes

Parameter a in the critical nitrogen concentration model represents the critical nitrogen concentration value when the plant biomass is 1 t hm^{-1}. Based on this experiment and previous research, it can be concluded that the magnitude of the parameters a and b constructed in the experiment is related to the temperature and sunshine duration factors. The average annual temperature in northern Argentina is 21.6 °C, and the average temperature during potato planting is about 20 °C. The average sunshine hours of the potato growing period is 10 h. Zhang et al. (2020) [32] conducted an experiment in Inner Mongolia, China, where the average highest temperature was 27 °C, while the average lowest temperature was above 15 °C. The average sunshine hours of the potato growing period was 14 h. Peng's experiment was conducted in May in Denmark, where the average temperature during the growth phase was above 14 °C. In the experiment, during the spring potato cultivation season, the highest temperature range was 15–25 °C, and the lowest temperature range was 5–15 °C. On the other hand, during the autumn potato cultivation season, the highest temperature range was 10–20 °C, and the lowest temperature range was −5–10 °C. The average temperatures during spring potato cultivation in 2022 were 17 °C, 20 °C, and 25 °C; the average temperatures during the autumn potato cultivation season in 2022 were 18 °C, 10 °C, and 5 °C. The total sunshine duration was 458.05 h in spring and 373.61 h in autumn. The environmental factors of the two varieties were basically the same except for temperature and sunshine duration, and the potato varieties used in the two experiments were the same. Therefore, it can be inferred that the parameters of the critical nitrogen curve are closely related to temperature and sunshine duration factors. Qiang et al. (2019) [40] reported that the relationship describing the continuous decrease in nitrogen concentration with the increase in dry matter can be expressed by parameter b, and its size is mainly affected by the relationship between carbon accumulation and nitrogen absorption. In this experiment, compared with autumn potato, the critical nitrogen concentration curve of spring potato shoots changed significantly with planting temperature and sunshine hours. The nitrogen concentration of spring potato was generally higher than that of autumn potato, and the nitrogen concentration decreased rapidly for autumn potato. Parameter a for spring potato was higher than that in autumn, and parameter b was lower than that in autumn. In the vegetative growth stage, the temperature, sunshine duration, and other climatic conditions in the growth period of potato in spring and autumn are similar, so there is little difference between biomass and nitrogen concentration. However, low temperatures and short sunshine duration at the root expansion stage cause shoot senescence of autumn potato, which decreases root nitrogen absorption capacity and speeds up the transportation of nitrogen from shoots to roots. At the same time, aboveground biomass decreased, resulting in lower nitrogen concentration. Therefore, the critical nitrogen concentration of the underground part of potatoes in autumn is higher than that of potatoes in spring (Figure 5). The critical nitrogen concentration curve of spring potato cannot be used to diagnose the nitrogen nutrition of autumn potato, which will be misdiagnosed as nitrogen deficiency for autumn potato in the production process.

4.3. The Relationship Between NNI and Yield

With the increase in nitrogen application rate, the yield of tubers first increases and then decreases. Although the yield under the N_3 treatment increased compared to the N_0 treatment, it decreased by 41.6% compared to the N_2 treatment. The yield difference between the N_1 and N_2 treatments was not significant. According to the decrease in N_3 yield, the nitrogen application rate between N_1-N_2 was the most suitable. The results are similar to other studies [41,42]. NNI can be used to predict crop yield. Compared to traditional crops with underground parts as harvesting organs, such as cotton [4,43], rice [44,45], wheat [46], corn [47,48], chili pepper [49], and tomatoes [50], the nitrogen nutrition index based on the critical nitrogen concentration of the whole plant can better reflect the nitrogen nutrition status of potato. Many studies [24,31,51] have shown that the NNI can be used to estimate the yield. When the NNI of the whole plant is less than 1, potatoes are in a nitrogen-deficient state, and yield increases with the increase in nitrogen. In Figure 9, the relationship between NNI and RY (Relative Yield) was constructed. With the increase in N fertilizer application, RY reaches its maximum value under N_2 level treatment and the NNI nears 1. However, under the N_3 treatment, potato yield shows a decreasing trend and the NNI is higher than 1. Therefore, when the NNI approaches 1, the yield reaches its maximum, which is consistent with the research results of many scholars [40,52,53].

4.4. The S/R Ratio

The source–sink theory is an important theory for studying the growth process of plants. As a photosynthetic organ, the source can transfer photosynthetic products to other parts, and the ability of the sink to receive photosynthetic products also determines the final yield of the plant. A library with strong source-receiving capability can force the source to produce more photosynthetic products. A large reservoir and enough sources can greatly boost crop productivity. Nevertheless, achieving both parameters simultaneously is not feasible in real agricultural production activities. As a result, it is feasible to strike a balance between the source and the sink and maximize production potential. Many scholars have demonstrated through their own experiments that the application of nitrogen fertilizer can effectively control the balance between the source and sink [54]. Chen et al. (2020) [55] suggested that root elongation was inhibited by either N deficiency or excess. N deficiency can reduce root activity and water consumption and decrease reactive oxygen species (ROS) in roots, resulting in low root biomass accumulation. Excess N can increase aboveground organ growth and decrease root growth. Hisse et al. (2019) [56] pointed out that nitrogen deficiency leads to an imbalance between source and sink during the maize filling period, thereby affecting yield. Figure 10 shows that the crown root ratio shows a decreasing trend during the whole growth stage, which means that potatoes transport their photosynthetic products underground in the later stages of growth. On the other hand, the S/R ratio of potatoes increased first and then decreased with the increase in nitrogen levels, which is consistent with the viewpoint of Li et al. (2016) [18]. The potatoes with a higher S/R ratio in the early growth stage will obtain higher yields. In addition, the S/R ratio of spring potatoes in the early growth stage is higher than that of autumn potatoes, and the yield is also higher than that of autumn potatoes. This is because the S/R of autumn potatoes decreases under low-temperature stress conditions, leading to the premature transportation of photosynthetic products from aboveground to underground, thereby reducing yield. The S/R ratio of potatoes under various nitrogen treatment settings in the spring varies greatly, as Figure 10 illustrates. Potatoes grow more quickly in the early stages of development under normal temperature settings when the nitrogen application rate is increased. The S/R ratio is larger under high nitrogen conditions than it is under low nitrogen conditions [57]. Compared with spring potatoes, autumn potatoes were under adverse low temperatures and short sunshine duration conditions, which reduced their ability to absorb nitrogen and the pace at which their roots used it. This had an impact on the photosynthesis of the plants above the ground. The reduction in organic matter synthesized by photosynthesis leads to the restriction of the allocation of resources between the shoot part and the root part, and the plants are forced to transfer more synthetic organic matter from the shoot part to the root part in order to maintain the maximum nutrients of the plants [58], so the S/R ratio is reduced.

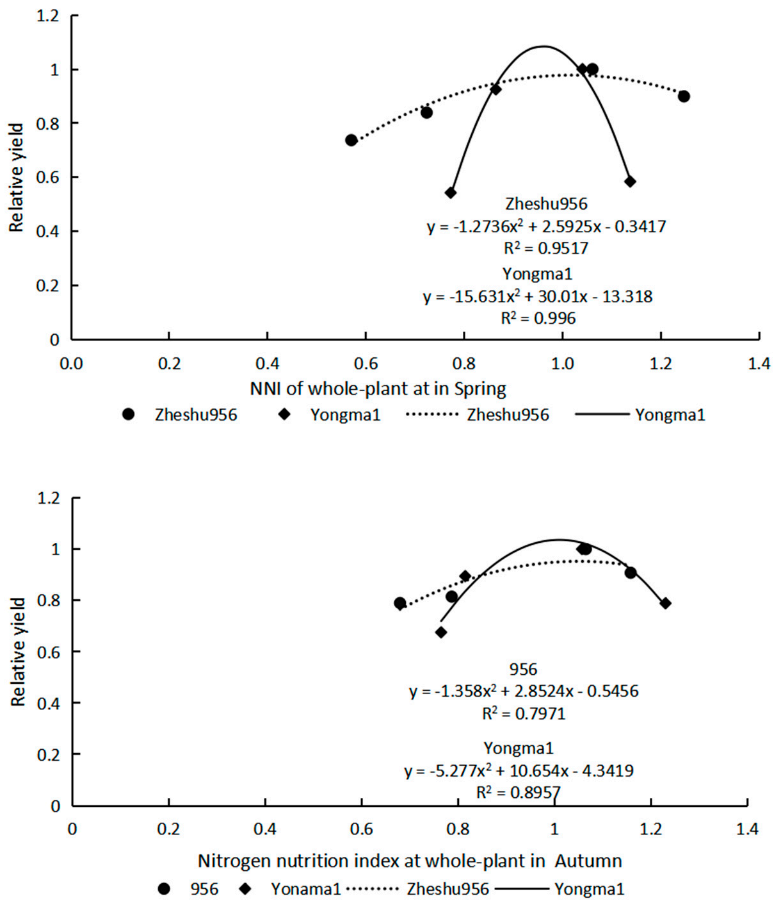

Figure 9. Relationship between relative yield (RY) and whole-plant nitrogen nutrition index (NNI) for Zheshu956 and Yongma1 in storage root expansion stage.

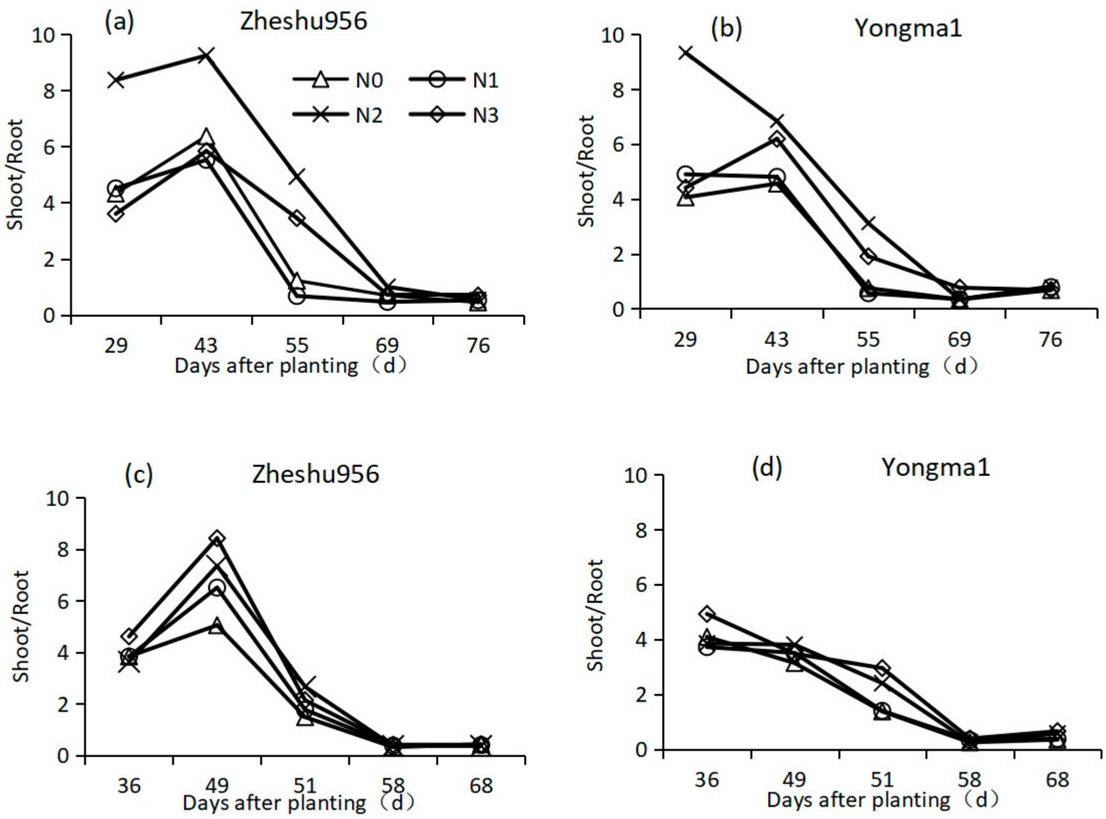

Figure 10. Dynamic change curve of the dry matter ratio of potato shoot–root with time (d, after transplantation) under different nitrogen application rates in spring Zheshu956 (**a**) and Yongma1 (**b**) potatoes and autumn Zheshu956 (**c**) and Yongma1 (**d**) potatoes.

5. Conclusions

The diagnosis of nitrogen nutrition in potatoes is of great significance for their fertilizer management. We constructed the critical nitrogen concentration dilution curve of spring and autumn potatoes for N diagnosis. The shoot, root, and whole-plant diluted nitrogen curve models of spring and autumn potatoes were different. For the shoot and the whole-plant nitrogen dilution curves, the spring potato curve model has a higher a value and a smaller b value than that of the autumn potato, resulting in a higher nitrogen concentration. The critical nitrogen concentration dilution curve based on the whole plant was determined to be more appropriate for tuber crops like potatoes. Furthermore, it is evident that NNI can be used to determine the amount of nitrogen that potatoes require. At N_2(160 kg ha^{-1}) level, both varieties achieved the maximum yield. The results of this study showed that the critical nitrogen concentration dilution curve model established in this experiment can be better applied to the diagnosis of the growth nitrogen requirement of spring and autumn potatoes. After two years of field experiments, we analyzed the influence of temperature and sunshine duration on the critical nitrogen concentration curve of potatoes in spring and autumn. However, in real life, two seasons also include other factors, so further supplementary verification is needed.

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References

1. Kahsay, W.S.; Tejada, M.M. Effects of nitrogen and phosphorus on potatoes production in ethiopia: A review. *Cogent Food Agric.* **2010**, *5*, 1572985. [CrossRef]
2. Cao, C.; Li, S.; Miao, F. Research progress on the effects of nitrogen on certain physiological and biochemical processes in plants. *D. Northwest A&F Univ.* **1999**, *4*, 99–104.
3. Huett, D.; White, E. Determination of critical nitrogen concentrations of potato (solanum tuberosum l. cv. sebago) grown in sand culture. *Aust. J. Exp. Agric.* **1992**, *32*, 765–772. [CrossRef]
4. Yin, X.; Main, C. Nitrogen fertilization and critical nitrogen concentration for contemporary high yielding cotton under no-tillage. *Nutr. Cycl. Agroecosyst.* **2015**, *103*, 359–373. [CrossRef]
5. Zhou, N. Effects of different nitrogen levels on potato yield composition and soil NO_3–N content. *Potatoes J.* **2010**, *24*, 91–93.
6. Jin, T.; Fan, M.; Zhou, D. Effects of drip irrigation with nitrogen application on yield, nitrogen absorption, and soil nitrate nitrogen accumulation of high ridge covered potatoes. *Plant Nutr. Fertil. Sci.* **2012**, *18*, 654–661.
7. Hou, X.; Zhang, F.; Hu, W. The effects of irrigation frequency and fertilization amount on the growth, yield, and nutrient absorption of drip irrigation potatoes. *Plant Nutr. Fertil. Sci.* **2019**, *25*, 85–96.
8. Liu, Y.; Chen, Q.; Tan, Q. Responses of wheat yields and water use efficiency to climate change and nitrogen fertilization in the north china plain. *Food Secur.* **2019**, *11*, 1231–1242. [CrossRef]
9. Shimono, H.; Fujimura, S.; Nishimura, T.; Hasegawa, T. Nitrogen uptake by rice (*Oryza sativa* L.) exposed to low water temperatures at different growth stages. *J. Agron. Crop Sci.* **2012**, *198*, 145–151. [CrossRef]
10. He, D.; Jia, L.; Qin, Y. Study on nitrogen utilization efficiency and classification of different potato varieties. *Crop J.* **2019**, *45*, 153–159.
11. Lv, Z.; He, W.; Lin, L.; Deng, L.; Yu, M.; Cong, W. Development of critical shoot and root N curves for diagnosing sweetpotato shoot and root N status. *Field Crop. Res.* **2020**, *257*, 107927. [CrossRef]
12. Bélanger, G.; Walsh, J.R.; Richards, J.E. Critical nitrogen curve and nitrogen nutrition index for potato in eastern Canada. *Am. J. Potato Res.* **2001**, *78*, 355–364. [CrossRef]
13. Abdallah, F.B.; Olivier, M.; Goffart, J.P.; Minet, O. Establishing the nitrogen dilution curve for potato cultivar Bintje in Belgium. *Potato Res.* **2016**, *59*, 241–258. [CrossRef]
14. Giletto, C.M.; Reussi, C.N.; ISandana, P.; Echeverria, H.E.; Belanger, G. Shoot-and tuber-based critical nitrogen dilution curves for the prediction of the n status in potato. *Eur. J. Agron.* **2020**, *119*, 126114. [CrossRef]
15. Zhou, Z.; Plauborg, F.; Liu, F.; Kristensen, K.; Andersen, M.N. Yield and crop growth of table potato affected by different split-n fertigation regimes in sandy soil. *Eur. J. Agron.* **2018**, *92*, 41–50. [CrossRef]
16. Giletto, C.M.; Echeverría, H.E. Critical nitrogen dilution curve in processing potato cultivars. *Am. J. Potato Res.* **2015**, *6*, 3144–3156. [CrossRef]
17. Bohman, B.J.; Culshaw-Maurer, M.; Abdallah, F.B.; Giletto, C.M.; Bélanger, G.; Fernández, F. Quantifying critical n dilution curves across G×E×M effects for potato using a partially-pooled bayesian hierarchical method. *Eur. J. Agron.* **2023**, *144*, 126744. [CrossRef]
18. Li, W.; Xiong, B.; Wang, S.; Deng, X.; Yin, L.; Li, H. Regulation Effects of Water and Nitrogen on the Source-Sink Relationship in Potato during the Tuber Bulking Stage. *PLoS ONE* **2016**, *11*, e0146877. [CrossRef] [PubMed]
19. He, Z.; Qiu, X.; Ata-Ul-Karim, S.T.; Li, Y.; Liu, X.; Cao, Q. Development of a Critical Nitrogen Dilution Curve of Double Cropping Rice in South China. *Front. Plant Sci.* **2017**, *8*, 638. [CrossRef]
20. Zhao, X. Establishment and Application of Critical Nitrogen Concentration Model for Post Flowering Leaf and Spike Organs of Winter Wheat. Master's Thesis, Henan Agricultural University, Zhengzhou, China, 2022.
21. Guo, B.; Zhao, X.; Meng, Y.; Liu, M.; Zhu, Y. Establishment of critical nitrogen concentration models in winter wheat under different irrigation levels. *Agronomy* **2020**, *10*, 556. [CrossRef]
22. Wang, H.; Hou, L.; Zhu, Y.; Zhang, Q.; Chen, L. Development of a critical nitrogen dilution curve of Siberian wildrye for seed production. *Field Crop. Res.* **2018**, *219*, 250–255. [CrossRef]
23. Yuen, S.H.; Pollard, A.G. Determination of nitrogen in soil and plant materials: Use of boric acid in the micro-kjeldahl method. *J. Sci. Food Agric.* **2010**, *4*, 490–496. [CrossRef]
24. Lv, Z.; Lu, G. A new curve of critical leaf potassium concentration based on the maximum root dry matter for diagnosing potassium nutritional status of sweet potato. *Front. Plant Sci.* **2021**, *12*, 714279. [CrossRef] [PubMed]
25. Song, X.; Xu, D.; Zhang, K.; Huang, S.; Guo, T.; Huang, C. Developing a critical nitrogen concentration dilution model and diagnosing nitrogen nutrition of wheat. *Soil. Sci. Plant Nutr.* **2022**, *22*, 4972–4982. [CrossRef]
26. Arash, R.; Ali, R.; Hamed, E. Determination of Critical Nitrogen Dilution Curve Based on Canopy Cover Data for Summer Maize. *Commun. Soil. Sci. Plant Anal.* **2020**, *51*, 2244–2256.

27. Greenwood, D.J.; Lemaire, G.; Gosse, G.; Cruz, P.; Draycott, A.; Neeteson, J.J. Decline in percentage n of C3 and C4 crops with increasing plant mass. *Ann. Bot.* **1990**, *66*, 425–436. [CrossRef]
28. Lemaire, G.; Salette, J. Relationship between growth and nitrogen uptake in a pure grass stand.1. environ. Eff. (Fr.). *Agronomie* **1984**, *4*, 423–430. [CrossRef]
29. Zhuang, H.; Ye, Y.; Zhao, K. A Review of Research on Crop Critical Nitrogen Concentration Dilution Models. *Chin. Soil Fertil.* **2013**, *1*, 220–229.
30. Xu, H.; Yao, B.; Wang, Q. Estimation of Rice Nitrogen Nutrient Index Based on Leaf Reflectance Spectra. *Chin. Agric. Sci. Bull.* **2021**, *54*, 4525–4538.
31. Deng, L.; Xu, X.; Zhu, Y.; He, W.; Jin, M.; Liu, Y. Changes in dilution curves of critical nitrogen concentration in sweetpotato under different potassium conditions. *Field Crop. Res.* **2023**, *303*, 109130. [CrossRef]
32. Zhang, J. Construction and Application of Critical Nitrogen Concentration Dilution Curves for Potatoes and Sugar Beets. Master's Thesis, Inner Mongolia Agricultural University, Hohhot, China, 2020.
33. Zhang, J.; Li, F.; Li, Y. Construction and validation of a critical concentration dilution model for potato nitrogen based on whole plant biomass and whole plant nitrogen concentration. *J. Plant Nutr.* **2020**, *26*, 1691–1701.
34. Peng, J.; Manevski, K.; Krup, K.; René, L.; Andersen, M.N. Random forest regression results in accurate assessment of potato nitrogen status based on multispectral data from different platforms and the critical concentration approach. *Field Crop. Res.* **2021**, *268*, 108–158. [CrossRef]
35. Zhang, K.; Wang, X.; Wang, X.; Ata-Ul-Karim, S.T.; Tian, Y.; Zhu, Y. Does the organ-based n dilution curve improve the predictions of n status in winter wheat. *Agriculture* **2020**, *10*, 500. [CrossRef]
36. Reyes, J.J.; Schellberg, J.; Siebert, S.; Adam, J.C.; Elsaesser, M.; Ewert, F. Improved estimation of nitrogen uptake in grasslands using the nitrogen dilution curve-reply to the letter to the editor by lemaire and gastal. *Agron. Sustain. Dev.* **2016**, *36*, 51. [CrossRef]
37. Hoogmoed, M.; Neuhaus, A.; Noack, S.; Sadras, V.O. Benchmarking wheat yield against crop nitrogen status. *Field Crop. Res.* **2018**, *222*, 153–163. [CrossRef]
38. Du, L.; Li, Q.; Li, L. Construction of a critical nitrogen dilution curve for maize in Southwest China. *J. Sci. Rep.* **2020**, *10*, 13084. [CrossRef]
39. Prystupa, P.; Ferraris, G.; Ventimiglia, L.; Loewy, T.; Couretot, L.; Bergh, R. Environmental control of malting barley response to nitrogen in the Pampas, Argentina. *Int. J. Plant Prod.* **2018**, *12*, 127–137. [CrossRef]
40. Qiang, S.; Zhang, F.; Zhang, Y. Modeling of critical nitrogen dilution curve for winter wheat in the Guanzhong Plain. *Agric. Res. Arid Areas* **2019**, *37*, 83–90.
41. Cai, L.; Gong, D.; Ding, R. The effect of nitrogen application level on the growth and yield of different potato varieties. *China Melon Veget.* **2023**, *36*, 84–90.
42. Yang, J.; Wei, W.; Hao, X. The effects of different water and nitrogen strategies on potato yield, quality, and water and nitrogen utilization. *J. Jiangsu Agric. Sci.* **2023**, *51*, 95–101.
43. Wang, X.; Dong, X.; Yu, Y. Diagnosis of nitrogen nutrition and yield estimation of cotton under drip irrigation in southern Xinjiang based on critical nitrogen concentration. *J. Appl. Ecol.* **2023**, *34*, 688–698.
44. He, Z. Construction of a Critical Nitrogen Concentration Dilution Model for Double Cropping Rice and Research on Nitrogen Diagnosis. Master's Thesis, Nanjing Agricultural University, Nanjing, China, 2016.
45. Lu, Z. A Study on the Critical Nitrogen Concentration and Spectral Index Model of Rice in the Lower Reaches of the Yangtze River. Master's Thesis, Nanjing Agricultural University, Nanjing, China, 2015.
46. Xu, X.; Bai, R.; Ai, H. Diagnosis of nitrogen nutrition in winter wheat under drip irrigation in the Ta'e Basin, Xinjiang. *China Soils Fertil.* **2023**, 1–9. [CrossRef]
47. Zhang, W.; Gao, Y.; Tang, Y. Construction and validation of a critical nitrogen concentration dilution model for corn in central and western. *Inn. Mong. Agric. Univ.* **2020**, *28*, 2020–2029.
48. Maccari, M.; Assmann, T.S.; Bernardon, A.; André, B.S.; Glienke, C.L. Relationships between n, p, and k in corn biomass for assessing the carryover effects of winter pasture to corn. *Eur. J. Agron.* **2021**, *129*, 126317. [CrossRef]
49. Xiao, R. Research on nitrogen nutrition diagnosis of chili based on critical nitrogen concentration dilution curve model. *China Veget.* **2023**, *1*, 90–97.
50. Wang, X.; Ma, F.; Diao, M. Simulation of critical nitrogen concentration, nitrogen absorption, and nitrogen nutrient index in tomato under drip irrigation. Trans. *Chin. Soc. Agric. Eng.* **2013**, *18*, 99–108.
51. Errecart, P.M.; Agnusdei, M.G.; Lattanzi, F.A.; Marino, M.A. Leaf nitrogen concentration and chlorophyll meter readings as predictors of tall fescue nitrogen nutrition status. *Field Crop. Res.* **2012**, *129*, 46–58. [CrossRef]
52. Fu, J.; Jia, B.; Yang, W.; Wei, X.; Ma, C.; Liu, G. Development of critical nitrogen dilution curve based on leaf dry matter for maize under drip irrigation. *J. Appl. Ecol.* **2020**, *31*, 945–952.
53. Ma, X.; Zhang, X.; Huang, Y.; Ye, Y. Establishment and application of critical nitrogen dilution curve for wheat based on leaf dry matter. *J. Plant Physiol.* **2017**, *53*, 1313–1321.
54. Zhang, Z.; Xu, X.; Jin, M.; Bai, J.; Shu, X.; Deng, L. A new curve of critical leaf nitrogen concentration based on the maximum root dry matter for diagnosing nitrogen nutritional status of sweetpotato. *Eur. J. Agron.* **2024**, *156*, 127–176. [CrossRef]
55. Chen, J.; Liu, L.; Wang, Z.; Zhang, Y.; Sun, H.; Song, S. Nitrogen fertilization increases root growth and coordinates the root-shoot relationship in cotton. *Front. Plant Sci.* **2020**, *11*, 880. [CrossRef] [PubMed]

56. Hisse, I.R.; D'Andrea, K.E.; Otegui, M.E. Source-sink relations and kernel weight in maize inbred lines and hybrids: Responses to contrasting nitrogen supply levels. *Field Crop. Res.* **2019**, *230*, 151–159. [CrossRef]
57. Gao, K.; Yu, Y.; Xia, Z.; Yang, G.; Xing, Z.; Qi, L. Response of height, dry matter accumulation and partitioning of oat (*Avena sativa* L.) to planting density and nitrogen in horqin sandy land. *Sci. Rep.* **2019**, *9*, 7961. [CrossRef]
58. Lopez, G.; Ahmadi, S.; Amelung, W.; Athmann, M.; Ewert, F.; Gaiser, T. Nutrient deficiency effects on root architecture and root-to-shoot ratio in arable crops. *Front. Plant Sci.* **2023**, *13*, 1067498. [CrossRef] [PubMed]