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Effects of Nitrogen Fertilizer Management on Dry Matter Accumulation and Yield of Drip-Irrigated Sugar Beet in Arid Areas

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Abstract: Clarifying the optimal combination of N fertilizer application rate and application method can maximize the yield of drip-irrigated sugar beet in arid areas, which is of great significance for reducing farmland N pollution and achieving sustainable agricultural development. In this three-year field experiment in Xinjiang, China, the effects of three N application rates [75 kg ha^{-1} (N1), 150 kg ha^{-1} (N2), and 225 kg ha^{-1} (N3)] and three N application methods [the proportion of N applied at canopy rapid growth stage, taproot expansion stage, and sugar accumulation stage were (M_1) 100%: 0%: 0%, (M_2) 70%: 30%: 0%, and (M_3) 50%: 30%: 20%] on the dry matter accumulation (DMA) and distribution, leaf senescence, yield, and agronomic N use efficiency (aNUE) of drip-irrigated sugar beet were explored. The results showed that N application (N1, N2, and N3 treatments) increased the shoot DMA by 27.7% (three-year average), 52.6%, and 83.1%, and the taproot DMA by 28.3%, 43.2%, and 61.6%, respectively ($p < 0.05$), compared with CK (no N supply) treatment. The N application methods M_2 and M_3 increased the shoot DMA by 5.6% (three-year average) and 1.0% ($p > 0.05$), respectively, and the taproot DMA by 7.2% and 3.6% ($p < 0.05$), respectively, compared with M_1. In addition, M_2 could delay the end of shoot and taproot growth (t_e) and the occurrence of maximum growth rate (t_m). In particular, the N3M_2 treatment increased the leaf area index (LAI) by 20.4–75.9% ($p < 0.05$) compared with other treatments by increasing the leaf area duration (LAD) and decreasing the leaf senescence rate (LSR). The taproot yield and sugar yield of N3M_2 treatment reached the maximum at harvest time, but there was no significant difference in taproot yield and sugar yield between N3M_2 treatment and N2M_2 treatment. The aNUE in N2M_2 treatment was the highest ($p < 0.05$), which was 1.29–7.85 times higher than that of other treatments. Therefore, reducing the N application rate from 225 kg·ha^{-1} to 150 kg·ha^{-1} and applying 70% and 30% of 150 kg N ha^{-1} at the canopy rapid growth stage and the taproot expansion stage, respectively, could achieve the goal of increasing sugar beet yield and N use efficiency. This study will provide an important reference for the sustainable production of sugar beet under drip irrigation in Xinjiang, China.

Keywords: nitrogen application method; plant growth rate; leaf area duration; leaf senescence rate; agronomic nitrogen use efficiency

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1. Introduction

Sugar beet, native to the western and southern coasts of Europe, is an important sugar crop. The sugar produced from sugar beet accounts for 25% of the global sugar production [1]. In China, sugar beet is mainly grown in Xinjiang, Heilongjiang, and Inner Mongolia. Especially in the arid region of Xinjiang, the total yield of sugar beet exceeds more than 50% of the national total [2]. Sugar beet yield is closely related to climatic conditions, genotype, irrigation, N management, planting density, etc., and proper water and fertilizer management can improve the yield and water- and fertilizer-use efficiency of sugar beet [3]. However, in the arid areas of Xinjiang, farmers apply a large amount of N fertilizer or topdressing multiple times in pursuit of a high yield of sugar beet. This practice does not significantly improve yield but causes negative impacts such as low N use efficiency and N pollution [4,5]. Therefore, it is urgent to explore the optimal N fertilizer management to guide sugar beet production in Xinjiang.

Nitrogen fertilizer is an important factor for sugar beet to achieve high yield because N is an important component of protein, nucleic acid, chlorophyll, coenzyme, plant hormones, and secondary metabolites [6,7]. Some studies have shown that insufficient N supply can slow down taproot expansion and sucrose accumulation by reducing photosynthetic assimilate production and plant carbon and N metabolism, resulting in low yields. However, the overapplication of N can cause sugar beet shoots to grow vigorously and compete with taproots for photosynthetic assimilates, resulting in limited taproot growth and reduced taproot yield [8]. Overapplication of N can also reduce the sucrose content in the taproots, increase the impurity content (K^+, Na^+, and α-N content), and reduce the sugar yield and quality [9]. In addition, the overapplication of N may cause surface and groundwater pollution, increasing the risk of environmental pollution [10].

Some studies in Europe have found that under the Mediterranean climate, the optimal N application rate for sugar beet is 100–125 kg ha^{-1} which can achieve the highest yield and quality [11]. Other studies have found that under temperate continental climates, there is a quadratic relationship between sugar beet yield and N supply level, i.e., when N application rate exceeds 250 kg ha^{-1}, sugar beet yield will decrease [12]. In addition, several studies on N application rates for sugar beets under flood irrigation in North China have found that N application rates in the range of 150–180 kg/hm^2 not only increase taproot yield, but also improve N use efficiency by avoiding excessive N residues in the soil [13,14]. It is important to note that N supply needs to be synchronized with the N requirements of sugar beet plants [15]. Varga et al. [16] and Pospisil et al. [17] reported that sugar beets had a high N requirement from the seedling stage to the canopy rapid growth stage (from early June to the end of July), and sufficient N supply during these stages could accelerate leaf formation and canopy development, allowing plants to fully absorb and use the applied N, and reducing the risks of excessive N residue in the soil and N leaching. Conversely, the N requirement is low during the taproot expansion and sugar accumulation stages (middle and late growth stages). During these stages, plants can obtain sufficient N from the soil, so N fertilizer supply should be reduced at these stages to prevent canopy overgrowth and canopy competition with taproots for photosynthetic assimilates, and to avoid the excessive accumulation of impurities such as K, Na, and α-N in the taproots that hinder sugar extraction [16].

Nitrogen use efficiency is affected by irrigation patterns. Different from the traditional furrow irrigation and flood irrigation, the emerging drip fertigation technology can realize the simultaneous control of the fertilizer and water supply. This ensures the continuous optimal supply of water and nutrients to crops, and improves the absorption and utilization of fertilizers by crops [17]. Under furrow irrigation and flood irrigation, N fertilizer is generally applied 2–3 times for sugar beets. Under drip irrigation conditions, farmers applied N fertilizer more than five times during the sugar beet growth period, leading to the overgrowth of the canopy and late ripening. At present, the N use efficiency of drip-irrigated sugar beet in Xinjiang, China (38.3–55.3%), is lower than that of developed countries (40–60%) [18].

A large number of studies conducted in different climatic environments have clarified the N-requiring growth stages for sugar beet and the optimal N application rate. However, farmers in Xinjiang always apply more than 225 kg ha^{-1} of N fertilizer in sugar beet planting, which exceeds the N application rate recommended by scholars (150 kg ha^{-1}) [19,20]. In addition, farmers often implement multiple N topdressings through the drip irrigation system, but the yield and N use efficiency have not been significantly improved. Therefore, in this study, the optimal N application rate and N application method were determined to improve the growth, N use efficiency, and yield of sugar beet. The specific objectives were to explore (1) whether N reduction could affect sugar beet yield, and (2) the optimal combination of N application rate and N application method. This study will provide an important reference for the N management of drip-irrigated sugar beets in arid areas.

2. Materials and Methods

2.1. Experimental Site

This experiment was carried out in the Experimental Station of Agricultural College of Shihezi University (45°19′ N, 86°03′ E, 450.8 m a.s.l.) from 2016 to 2018. The experiment site has a temperate continental climate. The soil was gray desert soil. Table 1 shows properties of the surface soil (0–20 cm) [21]. To measure pH, 10.0 mg of soil was sieved through a 0.60 mm sieve and thoroughly mixed with 25 mL of deionized water. After 30 min, the pH of the supernatant was measured using a pH meter [S500-F, Mettler Toledo Technology Co., Ltd., Changzhou, China]. In addition, meteorological information including temperature, relative humidity, and precipitation was recorded daily during the sugar beet growth period (Figure 1). The previous crop planted in the experimental site was tomato.

Table 1. Soil properties in 2016–2018.

Year	pH (1:2.5)	Organic Matter Content (g kg^{-1})	Total Nitrogen Content (g kg^{-1})	Olsen-P (mg kg^{-1})	Available Potassium Content (mg kg^{-1})	Bulk Density (g cm^{-3})	Field Capacity (%)
2016	7.30 ± 0.02	13.27 ± 0.22	0.76 ± 0.03	22.56 ± 0.12	157.97 ± 1.47	1.45 ± 0.12	19.00 ± 0.59
2017	7.30 ± 0.01	13.25 ± 0.18	0.88 ± 0.05	22.60 ± 0.20	157.97 ± 2.17	1.52 ± 0.08	20.00 ± 0.85
2018	7.30 ± 0.03	13.24 ± 0.31	0.78 ± 0.01	22.47 ± 0.19	156.17 ± 2.98	1.48 ± 0.19	19.80 ± 0.34

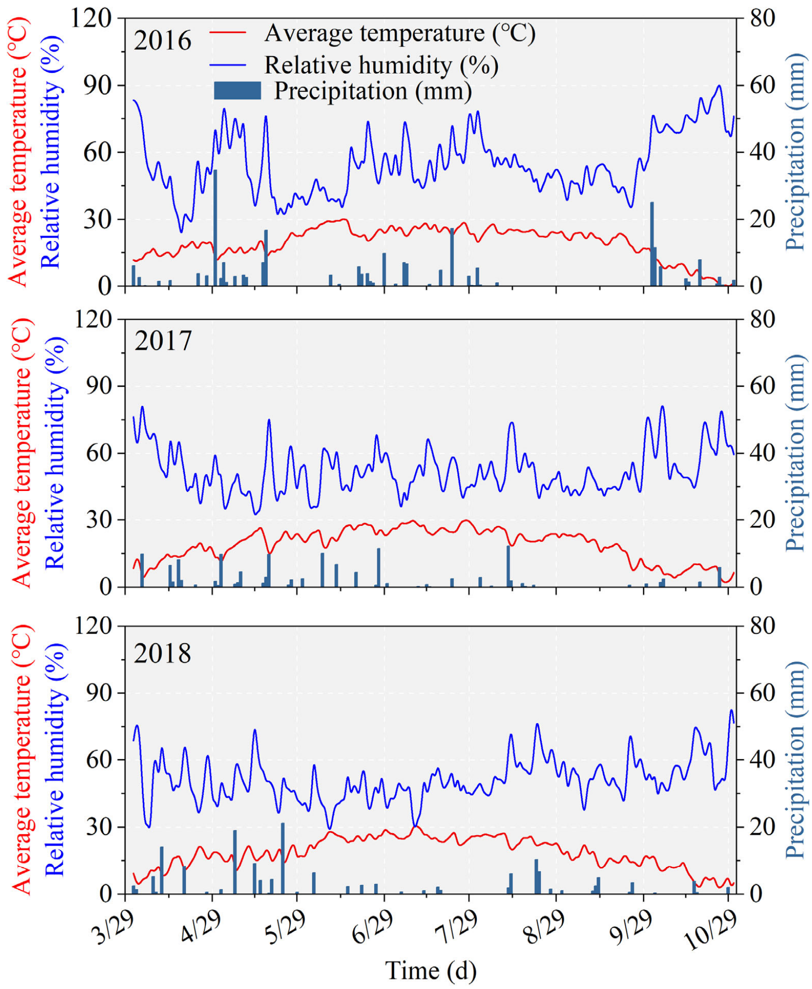

Figure 1. Precipitation (blue bar), daily average temperature (red line), and relative humidity (blue line) during sugar beet growth period in 2016–2018.

2.2. Experimental Design

A two-factor randomized complete block design was adopted. Firstly, three N application rates were designed; i.e., 75 (N1), 150 (N2), and 225 (N3) kg ha^{-1} of pure N were applied during the growth period of sugar beet. In 2016, under each N application rate, two split applications of N were designed; i.e., the proportions of N applied at the canopy rapid growth stage and the taproot expansion stage were (M_1) 100%:0% and (M_2) 70%:30%. In 2017 and 2018, under each N application rate, three split applications of N were designed; i.e., the proportions of N applied at canopy rapid growth stage, taproot expansion stage, and sugar accumulation stage were (M_1) 100%:0%:0%, (M_2) 70%:30%:0%, and (M_3) 50%:30%:20%. The treatment without N supply was used as the control (CK). Each treatment had three replicates. The area of each plot was 24 m^2 (4 m $\times$ 6 m), and the plot spacing was 1 m. The sugar beet row spacing was 50 cm, and the plant spacing was 20 cm. The sowing density was 1×10^5 plants ha^{-1}. Sugar beet seeds were sown on 18 April 2016, 16 April 2017, and 19 April 2018. Sugar beet taproots were harvested on 2 October 2016, 6 October 2017, and 4 October 2018. All phosphorus (P) and potassium (K) fertilizers were mixed and applied before sowing (P_2O_5: 147 kg ha^{-1}; K_2O: 105 kg ha^{-1}). N fertilizer (urea) was applied with irrigation water through the drip irrigation system, according to the experimental design (Table 2). Due to the large amount of N fertilizer applied in the canopy rapid growth stage, the N fertilizer for this stage was divided into two parts and applied separately in this stage. For the other stages, the N fertilizer was applied once. Drip irrigation was adopted, and one drip tape was laid in the middle of two plant rows. Irrigation was conducted eight times during the growth period of sugar beets, and the total irrigation amount for each treatment was 7500 m^3/hm^2. Other agricultural managements were consistent with those in local fields, i.e., to prevent the growth of weeds, s-metolachlor was sprayed into the soil before sowing and weeds were pulled by hand at regular intervals after the emergence of sugar beets. Chlorantraniliprole and thiophanate-methyl were sprayed at 55, 85, and 115 days after the emergence of sugar beets to prevent insect and disease infestation.

Table 2. Application time and amount of nitrogen fertilizer (kg/hm^2).

	Stage	**Canopy Rapid Growth Stage**		**Taproot Expansion Stage**	**Sugar Accumulation Stage**
	Date	4 June 2016	13 June 2016	1 July 2016	1 August 2016
	CK	0		0	/
N1	M_1	37.50	37.50	0	/
	M_2	26.25	26.25	22.50	/
N2	M_1	75.00	75.00	0	/
	M_2	52.50	52.50	45.00	/
N3	M_1	112.50	112.50	0	/
	M_2	78.75	78.75	67.50	/
	Date	14 June 2017	25 June 2017	25 July 2017	25 August 2017
	CK	0		0	0
	M_1	37.50	37.50	0	0
N1	M_2	26.25	26.25	22.50	0
	M_3	18.75	18.75	22.50	15.00
	M_1	75.00	75.00	0	0
N2	M_2	52.50	52.50	45.00	0
	M_3	37.50	37.50	45.00	30.00
	M_1	112.50	112.50	0	0
N3	M_2	78.75	78.75	67.50	0
	M_3	56.25	56.25	67.50	45.00
	Date	17 June 2018	28 June 2018	21 July 2018	25 August 2018
	CK	0		0	0
	M_1	37.50	37.50	0	0
N1	M_2	26.25	26.25	22.50	0
	M_3	18.75	18.75	22.50	15.00
	M_1	75.00	75.00	0	0
N2	M_2	52.50	52.50	45.00	0
	M_3	37.50	37.50	45.00	30.00
	M_1	112.50	112.50	0	0
N3	M_2	78.75	78.75	67.50	0
	M_3	56.25	56.25	67.50	45.00

2.3. Leaf Area Index, Leaf Area Duration, and Leaf Senescence Rate

Destructive sampling (five plants for each treatment) was performed at each growth stage (35, 65, 98, 130, and 155 days after emergence in 2016; 33, 61, 102, 135, and 162 days after emergence in 2017; 40, 59, 87, 117, and 160 days after emergence in 2018). The collected five plant samples for each treatment were separated into leaves, petioles, and taproots. The LAI of each stage was measured using a Li-3100C leaf area meter (Li-Cor, Lincoln, LA, USA), and the leaf area duration (LAD) ($m^2\ d^{-1}$) and leaf senescence rate (LSR) ($cm^2\ d^{-1}$) were calculated according to the following formulas [22]:

$$\mathrm{LAD} = \frac{(\mathrm{LA_a} + \mathrm{LA_b}) \times (\mathrm{T_b} - \mathrm{T_a})}{2} \quad (1)$$

$$\mathrm{LSR} = \frac{\mathrm{LA_a} - \mathrm{LA_b}}{\mathrm{T_b} - \mathrm{T_a}} \quad (2)$$

where $\mathrm{LA_a}$ and $\mathrm{LA_b}$ represent the leaf areas measured at two consecutive sampling time points. $\mathrm{T_a}$ and $\mathrm{T_b}$ represent two consecutive sampling time points. In this study, the LAD at each sampling time point was calculated. In the three years, the leaf area reached its largest value 100 days after emergence and then began to decline, so the leaf senescence rate after the occurrence of the maximum leaf area was calculated in this study.

2.4. Fitting of Dry Matter Accumulation Dynamics

In this study, the leaves, petioles, and taproots of five plants for each treatment after LAI measurement were dried in an oven at 105 °C for 30 min, and then dried to a constant weight at 80 °C, followed by weighing to obtain the dry matter accumulation (DMA). Then, the univariate nonlinear regression equation was used to fit the shoot and taproot DMA dynamics. Based on the fitting results, the maximum DMA (W_{max}), the occurrence time of the maximum DMA (t_e), the maximum DMA rate (C_m), and the occurrence time of the maximum DMA rate (t_m) were calculated [23,24]. The dynamics of the relationship between the shoot and taproot DMA of sugar beet were as follows:

$$w = w_{max}\left(1 + \frac{t_e - t}{t_e - t_m}\right)\left(\frac{t}{t_e}\right)^{\frac{t_e}{t_e - t_m}} \quad (3)$$

The sugar beet growth rate over the entire growth period was calculated with the following equations:

$$\frac{d_w}{d_t} = c_m\left(\frac{t_e - t}{t_e - t_m}\right)\left(\frac{t}{t_m}\right)^{\frac{t_m}{t_e - t_m}} \quad (4)$$

$$c_m = w_{max}\left(\frac{2t_e - t}{t_e(t_e - t_m)}\right)\left(\frac{t_m}{t_e}\right)^{\frac{t_m}{t_e - t_m}} \quad (5)$$

Finally, by calculating the ratio of the daily DMA of the shoot or taproot to the sum of the two, the assimilate partitioning indexes (PIs) of the shoot and taproot were obtained [23].

$$\mathrm{PI_i} = \frac{\mathrm{dw_i/dt}}{\mathrm{dw_a/dt}} \quad (6)$$

where $\mathrm{dw_i/dt}$ denotes the daily DMA dynamics of the shoot or taproot, and $\mathrm{dw_a/dt}$ denotes the sum of the daily DMA of the shoot and taproot.

2.5. Yield and Sugar Content Determination

During the harvest period of 2016, 2017, and 2018, five sugar beets in the center of each plot (5 m^2) were collected. The shoots were removed, and the soil on the taproots was removed by washing. Then, the taproots were weighed by an electronic scale to obtain the taproot yield per unit area. After that, nine sugar beet plants were selected from each plot. The refractive index was determined using a portable digital refractometer (ATAGO, Tokyo, Japan), and then it was multiplied by a correction coefficient (0.83) to obtain the sugar content. Taproot yield (TY) was calculated using Equation (7). Sugar yield (SY) was calculated using Equation (8).

$$\text{Taproot yield}\left(\text{TY, kg ha}^{-1}\right) = \text{taproot yield per area} \times \text{planting area} \tag{7}$$

$$\text{Sugar yield}\left(\text{SY, kg ha}^{-1}\right) = \text{TY} \times \text{sugar content} \tag{8}$$

In addition, based on the final SY and the N application rate, the agronomic N use efficiency (aNUE) (kg/kg) was calculated using Equation (9) [25].

$$\text{aNUE (kg/kg)} = \left(\text{SY}_{\text{appl}} - \text{SY}_{\text{N0}}\right)/\text{N}_{\text{appl}} \tag{9}$$

where SY_{appl} denotes the sugar yield in the N application treatment at harvest time, SY_{CK} denotes the sugar yield in the CK treatment at harvest time, and N_{appl} denotes the N application rate (75, 150, and 225 kg ha^{-1}).

2.6. Data Analysis

The least significance difference (LSD) test at the 5% and 1% levels was conducted to determine whether the difference between the mean values of the treatments (N treatment and M treatment) was significant based on SPSS 25.0 software (SPSS Inc., Chicago, IL, USA). In addition, the nonlinear regression of the sugar beet growth dynamics was completed by SPSS 25.0 software. The data visualization was completed by Origin 2024 (Originlab, Northampton, MA, USA).

3. Results

3.1. Dry Matter Accumulation Dynamics of Sugar Beet Shoots under Different N Fertilizer Management

The DMA in the shoots of sugar beet increased first and then decreased over time, and the DMA was the highest about 80–120 days after emergence. Compared with the CK treatment, N application (N1, N2, and N3 treatments) increased the DMA of shoots by increasing the DMA rate in the shoots, and the DMA and DMA rate in the shoots increased with the increase in the N application rate, and decreased significantly 120 days after emergence ($p < 0.05$). At the harvest time, the shoot DMA of N1, N2, and N3 treatments increased by 28.1% (three-year average), 53.1%, and 83.0%, respectively ($p < 0.05$), compared with that of CK treatment. The comparison of M_1, M_2, and M_3 treatments showed that compared with M_1 treatment, M_2 treatment increased the shoot DMA, especially under a high N application rate (N3). However, the M_3 treatment did not further improve the shoot DMA. At a three-year harvest time, the DMA of N3M_2 treatment increased by 3.7% (three-year average) and 5.4% compared with that of the N3M_1 and N3M_3 treatments, respectively ($p < 0.05$) (Figure 2).

3.2. Dry Matter Accumulation Dynamics of Sugar Beet Taproots under Different N Fertilizer Managements

The DMA of sugar beet taproots increased over time, and was the highest at harvest time. However, the DMA rate of sugar beet taproots decreased over time, and the taproot growth stopped about 140–160 days after emergence. Compared with the CK treatment, N application (N1, N2 and N3 treatments) increased the DMA and DMA rate in sugar beet taproots ($p < 0.05$), and the DMA and DMA rate increased with the increase in the N application rate. At a three-year harvest time, the taproot DMA of the N1, N2, and N3 treatments increased by 27.5% (three−year average), 42.2%, and 59.4%, respectively ($p < 0.05$), compared with that of the CK treatment. In addition, the M_2 treatment increased the taproot DMA of sugar beet at the harvest time by increasing the growth rate of sugar beet, especially under a high N application rate (N3). The DMA at the harvest time of

N3M$_2$ treatment increased by 8.9% and 6.1% ($p < 0.05$) compared with that of N3M$_1$ and N3M$_3$ treatment, respectively (Figure 3).

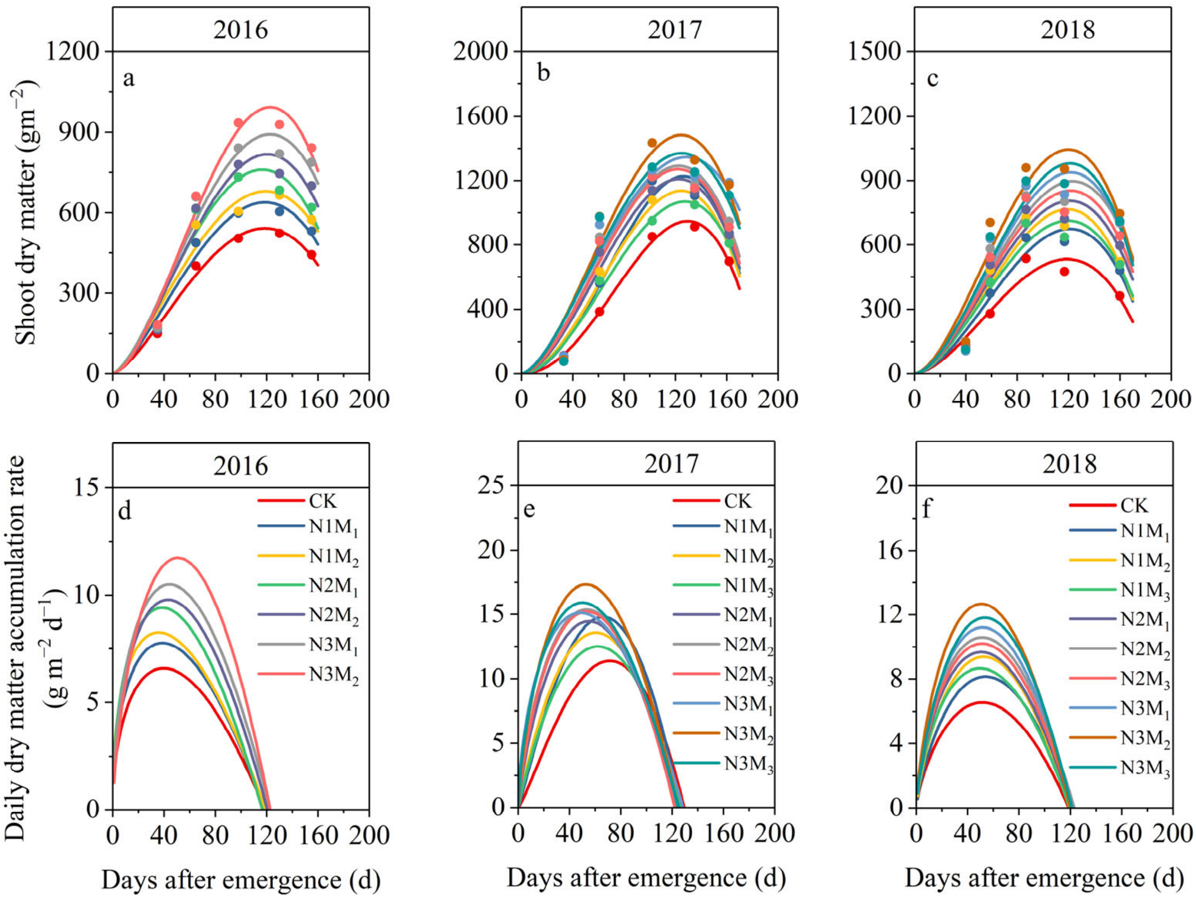

Figure 2. Dynamics of dry matter accumulation (**a**–**c**) and daily accumulation rate (**d**–**f**) in sugar beet shoots under different N application rates (CK, N1, N2, and N3) and N application methods (M$_1$, M$_2$, and M$_3$) in 2016–2018. CK, 0 kg N ha^{-1}; N1, 75 kg N ha^{-1}; N2, 150 kg N ha^{-1}; N3, 225 kg N ha^{-1}; M$_1$ denotes that the proportions of N applied at the canopy rapid growth stage, taproot expansion stage, and sugar accumulation stage were 100%, 0%, and 0%, respectively; M$_2$ denotes that the proportions of N applied at the canopy rapid growth stage, taproot expansion stage, and sugar accumulation stage were 70%, 30%, and 0%, respectively; M$_3$ denotes that the proportions of N applied at the canopy rapid growth stage, taproot expansion stage, and sugar accumulation stage were 50%, 30%, and 20%, respectively. The same is seen below.

3.3. Dynamics of DMA in the Shoots and Taproots of Sugar Beet under Different N Fertilizer Managements

Shoot growth ended 118–128 days after emergence in the three years, and the maximum DMA rate of shoots occurred 40–50 days (2016), 53–71 days (2017), and 49–54 days (2018) after emergence. Similarly, taproot growth ended 137–159 days after emergence, and the maximum DMA rate of taproots occurred 85–93 days (2016), 53–71 days (2017), and 69–75 days (2018) after emergence. Compared with the CK treatment, N application (N1, N2, and N3 treatments) increased the DMA by increasing the growth rate of sugar beet. In particular, the N3M$_2$ treatment promoted the growth of sugar beet shoots and taproots ($p < 0.05$). The maximum DMA values in the shoots of the N3M$_2$ treatment were 893 g m^{-2} (2016), 1483 g m^{-2} (2017), and 1045 g m^{-2} (2018), which were 6.8–32.5% ($p < 0.05$) higher than those of other treatments. The maximum DMA values in the taproots of the N3M$_2$ treatment were 1943 g m^{-2} (2016), 2303 g m^{-2} (2017), and 1960 g m^{-2} (2018), which were 4.8–38.9% ($p < 0.05$) higher than those of the other treatments. The N3M$_2$ treatment increased the DMA in the shoots and taproots, compared with other treatments, by increasing the growth rate in the shoots and taproots and delaying the occurrence of the maximum DMA rate and the plant growth end time (Table 3).

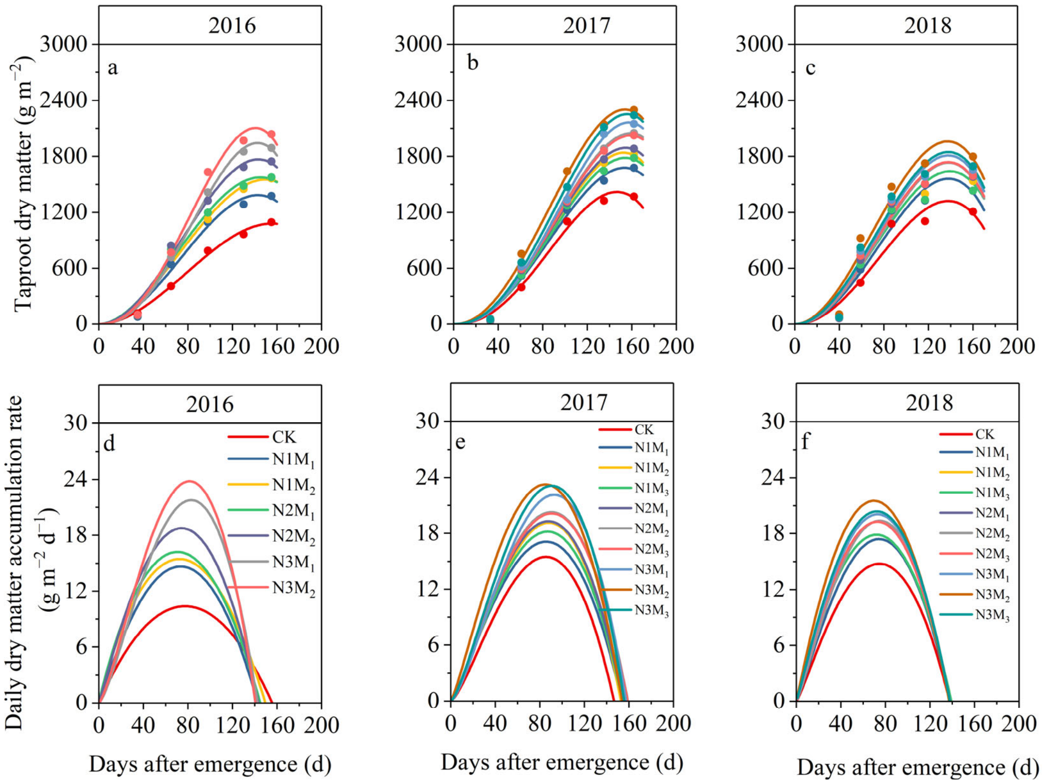

Figure 3. Dynamics of dry matter accumulation (**a**–**c**) and daily accumulation rate (**d**–**f**) in sugar beet taproots under different N application rates (CK, N1, N2, and N3) and N application methods (M_1, M_2, and M_3) in 2016–2018.

Table 3. Fitting parameters of dry matter accumulation in the shoots and taproots of sugar beet under different N application rates and N application methods in 2016–2018.

Year	Treatment	Shoot				Taproot			
		W_{max} (g/m^2)	t_e (d)	t_m (d)	C_m (g/m^2 d)	W_{max} (g/m^2)	t_e (d)	t_m (d)	C_m (g/m^2 d)
2016	CK	541.6 d	118.7 b	39.7 bc	6.6 c	1078.8 c	155.7 a	77.5 b	10.4 d
	N1M$_1$	638.4 cd	118.7 b	38.7 bc	7.8 bc	1384.4 b	142.8 b	73.3 bc	14.7 c
	N1M$_2$	680 c	119.3 ab	35.9 c	8.3 b	1553.4 ab	149.6 b	72.5 c	15.5 bc
	N2M$_1$	760.6 bc	116.6 b	38.6 bc	9.4 ab	1577 ab	144.9 b	70.6 c	16.2 b
	N2M$_2$	818.3 b	120.6 a	43.1 b	9.8 ab	1414.9 b	143.2 b	74.3 bc	15.0 bc
	N3M$_1$	893.1 ab	122.7 a	44.3 b	10.5 a	1554.4 ab	142.5 b	82.9 a	17.4 ab
	N3M$_2$	994.2 a	122.8 a	50.7 a	11.8 a	1682.8 a	140.7 b	81.4 a	19.0 a
2017	CK	947.7 c	129.5 a	71.4 a	11.4 c	1419.3 e	146.6 d	85.5 c	15.4 e
	N1M$_1$	1226.5 b	126.2 a	66.2 ab	14.8 b	1678.9 d	153.5 bc	85.7 bc	17.1 d
	N1M$_2$	1136.4 bc	124.6 a	60.7 b	13.6 bc	1839.8 c	152.8 c	88.0 b	19.1 c
	N1M$_3$	1068.8 bc	127.5 a	62.2 b	12.5 c	1785.1 cd	154.3 b	87.1 b	18.2 cd
	N2M$_1$	1209.8 b	122.7 a	55.2 c	14.5 b	1891.3 c	154.5 b	87.6 b	19.3 bc
	N2M$_2$	1291.6 b	122.6	53.3 c	15.4 ab	2046.8 b	159.1 a	90.3 ab	20.2 b
	N2M$_3$	1271.0 b	122.0 a	53.6 c	15.2 ab	2023.2 bc	158.7 a	90.6 ab	20.2 b
	N3M$_1$	1346.2 ab	128.6 a	48.6 d	15.1 ab	2163.1 b	157.4 a	93.0 a	22.2 ab
	N3M$_2$	1483.5 a	124.6 a	52.9 c	17.3 a	2303.3 a	153.9 b	85.0 c	23.3 a
	N3M$_3$	1370.6 ab	124.8 a	50.2 cd	15.9 ab	2253.8 ab	155.8 ab	90.7 ab	23.1 a

Table 3. *Cont.*

Year	Treatment	Shoot W_{max} (g/m^2)	Shoot t_e (d)	Shoot t_m (d)	Shoot C_m (g/m^2 d)	Taproot W_{max} (g/m^2)	Taproot t_e (d)	Taproot t_m (d)	Taproot C_m (g/m^2 d)
2018	CK	533.0 d	118.9 b	51.5 ab	6.5 d	1320.9 d	137.7 a	74.6 a	14.8 c
	N1M$_1$	674.1 c	121.1 a	54.0 a	8.1 c	1562.1 c	138.0 a	74.3 a	17.4 b
	N1M$_2$	765.3 bc	119.3 b	52.5 a	9.4 b	1641.8 bc	139.2 a	72.0 a	17.9 b
	N1M$_3$	712.8 c	119.5 b	49.8 b	8.7 bc	1641.8 bc	139.2 a	72.0 a	17.9 b
	N2M$_1$	805.1 b	120.9 ab	50.6 b	9.7 b	1733.1 b	138.1 a	74.9 a	19.4 ab
	N2M$_2$	896.9 ab	123.1 a	51.4 ab	10.6 ab	1733.6 b	138.1	74.9 a	19.4 ab
	N2M$_3$	852.9	121.5 a	51.2 ab	10.2 ab	1738.7 b	137.8	72.8 a	19.3 ab
	N3M$_1$	938.1 a	121.7 a	51.7 ab	11.2 a	1810.3 ab	137.9 a	73.0 a	20.1 a
	N3M$_2$	1045.0 a	120.0 ab	50.8 b	12.7 a	1960.1 a	137.3 a	69.7 b	21.5 a
	N3M$_3$	979.9 a	121.3 a	53.4 a	11.8 a	1846.7 ab	137.9 a	72.3 a	20.4 a

W_{max}, maximum DMA (g/m^2); t_e, occurrence time of the maximum DMA (d); t_m, occurrence time of the maximum DMA rate (d); C_m, maximum DMA rate (g/m^2 d). CK, 0 kg N ha^{-1}; N1, 75 kg N ha^{-1}; N2, 150 kg N ha^{-1}; N3, 225 kg N ha^{-1}; M_1 denotes that the proportions of N applied at the canopy rapid growth stage, taproot expansion stage, and sugar accumulation stage were 100%, 0%, and 0%, respectively; M_2 denotes that the proportions of N applied at the canopy rapid growth stage, taproot expansion stage, and sugar accumulation stage were 70%, 30%, and 0%, respectively; M_3 denotes that the proportions of N applied at the canopy rapid growth stage, taproot expansion stage, and sugar accumulation stage were 50%, 30%, and 20%, respectively. The same is seen below. Different lowercase letters indicate a significant difference at $p < 0.05$ according to the Duncan test.

3.4. Assimilate Partitioning Index of Shoots and Taproots of Sugar Beet under Different N Fertilizer Management

The PI of sugar beet shoots decreased over time in the three years, while that of taproots increased over time. In the three years, 38–50 days (2016), 25–65 days (2017), and 22–47 days (2018) after emergence, the growth rate of the taproots was larger than that of the shoots, so the DMA in the taproots was higher than that in the shoots. At harvest time, the *PI* of sugar beet taproots was highest 68–73% (2016), 75–81% (2017), and 71–83% (2018), while that of the shoots was lowest 27–32% (2016), 11–25% (2017), and 17–19% (2018). Although postponed application of part of the total N fertilizer to the taproot expansion stage and the sugar accumulation stage (N2M$_2$, N2M$_3$, N3M$_2$, N3M$_3$) increased the DMA rate and DMA in the shoots and taproots, the PI (especially the PI of taproots) was not significantly improved (Figure 4).

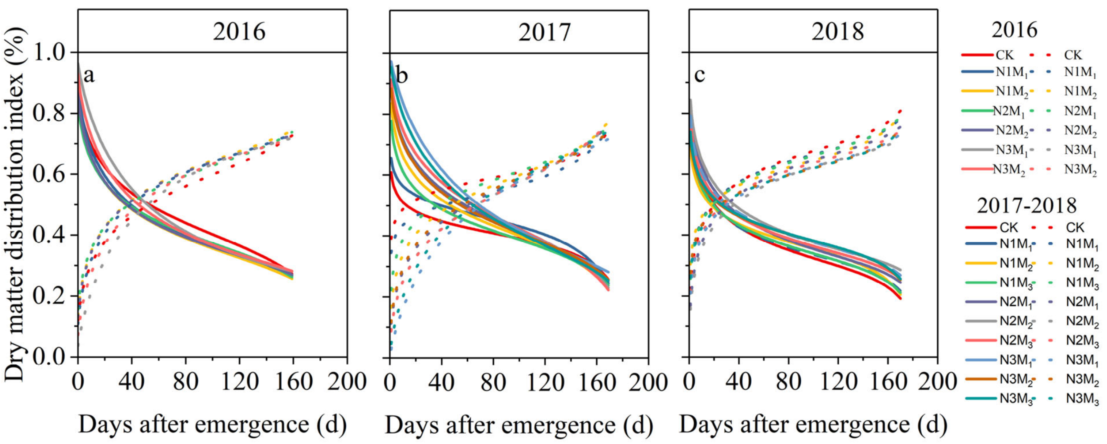

Figure 4. Assimilate partitioning index (PI) of sugar beet shoots (solid line) and taproots (dashed line) under different N application rates (CK, N1, N2, and N3) and N application methods (M_1, M_2, and M_3) during the sugar beet growth period in 2016–2018 (**a**–**c**).

3.5. Leaf Growth Dynamics of Sugar Beet under Different N Fertilizer Management

The LAI and LAD of sugar beet first increased and then decreased over time. The LAI was the highest about 100 days after emergence over the three years [2.3–5.1 (2016), 3.1–5.9 (2017) and 2.1–5.6 (2018)]. Similarly, the LAD was the highest in the middle and late stages (100–130 days after emergence) in the three years [72.6–135.1 m^2 d^{-1} (2016), 103.2–215.7 m^2 d^{-1} (2017) and 82.1–195.6 m^2 d^{-1} (2018)]. Nitrogen application increased the LAI and LAD of sugar beet at different growth stages, especially the N3M$_2$ treatment ($p < 0.05$). During the period with the highest LAI and LAD (100–130 days after emergence), the LAI of the N3M$_2$ treatment increased by 19.2–55.3% (2016), 22.5–72.7% (2017), and 19.4–99.6% (2018) ($p < 0.05$), and the LAD increased by 19.7–62.3% (2016), 22.9–75.1% (2017), and 17.4–97.6% (2018) ($p < 0.05$), compared with those of other treatments. Nitrogen application delayed canopy senescence by reducing the leaf senescence rate compared with CK treatment. In addition, compared with M$_1$ treatment, postponed application of part of the N fertilizer to the taproot expansion stage (M$_2$ and M$_3$ treatments) could further reduce the leaf senescence rate (Figure 5).

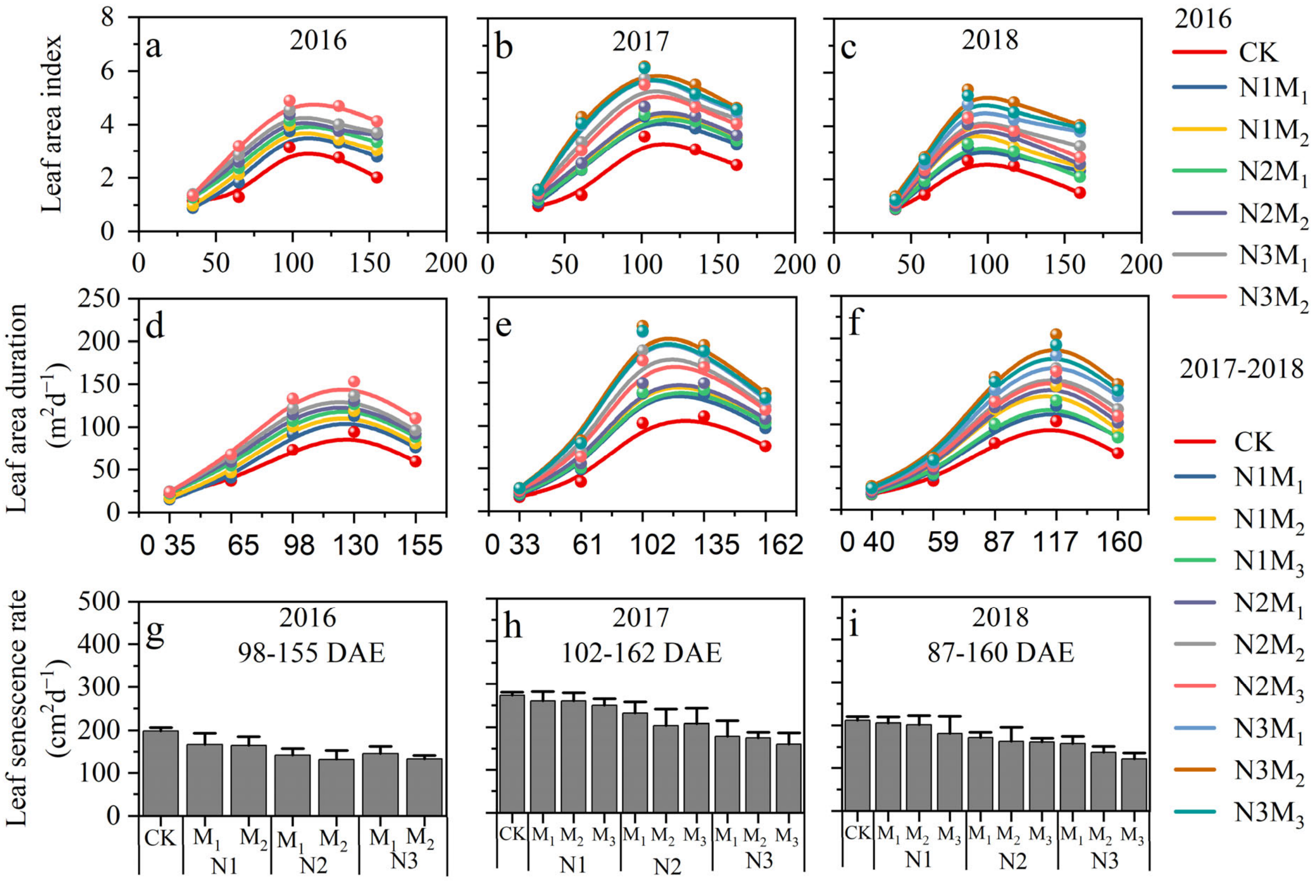

Figure 5. Effects of different N application rates (CK, N1, N2, and N3) and N application methods (M$_1$, M$_2$, and M$_3$) on the leaf area index (**a**–**c**), leaf area duration (**d**–**f**), and leaf senescence rate (**g**–**i**) of sugar beet in 2016–2018. Leaf area index and leaf area duration were measured at each growth stage (i.e., 35, 65, 98, 130, and 155 days after emergence (DAE) in 2016; 33, 61, 102, 135 and 162 DAE in 2017; 40, 59, 87, 117, and 160 DAE in 2018). Leaf area duration was measured for each growth stage (0–35, 36–65, 66–98, 99–130, and 131–155 DAE in 2016; 0–33, 34–61, 62–102, 103–135 and 136–162 DAE in 2017; 0–40, 41–59, 60–87, 88–117, and 118–160 DAE in 2018). Leaf senescence rate was calculated when the leaf area began to reduce after reaching the maximum (i.e., 98 DAE in 2016; 102 DAE in 2017; 87 DAE in 2018).

3.6. Agronomic Nitrogen Use Efficiency (aNUE) in Sugar Beet at Harvest Time under Different N Fertilizer Management

In 2016–2018, the aNUE in all treatments increased first and then decreased with the increase in N fertilizer application rate (Figure 6). In 2016, the aNUE of the N2M$_2$ treatment increased by 42.2% ($p < 0.05$) compared with that of the N2M$_1$ treatment. In 2018, the aNUE of the N2M_2 treatment increased by 60.8% and 98.7% compared with that of the N2M_1 and N2M_2 treatments, respectively ($p < 0.05$). There was no difference in the aNUE between the M_1, M_2, and M_3 treatments under N1 and N3 nitrogen application levels ($p > 0.05$).

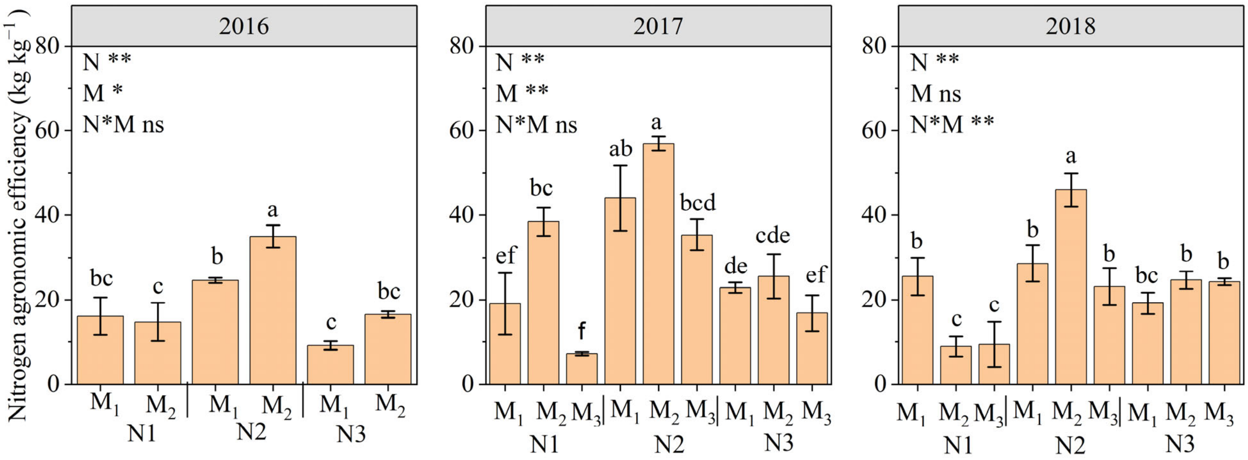

Figure 6. Effects of different N application rates (N1, N2, and N3) and N application methods (M_1, M_2, and M_3) on the agronomic nitrogen use efficiency of sugar beet in 2016–2018. Different lowercase letters indicate a significant difference at $p < 0.05$ according to the Duncan test. *, $p < 0.05$; **, $p < 0.01$; ns, $p > 0.05$.

3.7. Taproot Yield, Sugar Yield, and Sugar Content of Harvested Sugar Beets under Different N Fertilizer Management

Compared with the CK treatment, N application ($p < 0.05$) increased the TY and SY, especially the N3M_2 treatment, but there was no difference between N3M_2 treatment and N2M_2 treatment ($p > 0.05$) (Table 4). Although N2M_2, N2M_3, N3M_2, and N3M_3 treatments increased the TY and SY, they did not increase the sugar content of sugar beets over the three years ($p > 0.05$), and even reduced the sugar content in the taproots ($p > 0.05$), compared with the CK treatment (2016). In 2016 and 2018, the N3M_2 treatment had the highest TY, which was 5.5–68.3% (2016) and 1.5–63.4% (2018), higher than that of other treatments ($p < 0.05$). The N2M_2 treatment had the highest SY, which was 11.7–53.0% and 9.3–71.9% higher than that of other treatments, but there was no difference between N2M_2 treatment and N3M_2 treatment ($p > 0.05$). In 2017, the N2M_2 treatment had the highest TY and SY values, which were 5.6–72.7% and 16.5–75.3% ($p < 0.05$) higher than the other treatments, respectively.

Table 4. Sugar content, taproot yield, and sugar yield of sugar beet at harvest time under different N application rates (CK, N1, N2, N3) and N application methods (M_1, M_2, M_3) in 2016–2018.

Year	Treatment	Sugar Content (%)	Taproot Yield (t/ha)	Sugar Yield (t/ha)
2016	CK	16.9 ± 2.0 a	59.2 ± 4.1 f	10.0 ± 0.7 b
	N1M_1	16 ± 1.0 ab	70.1 ± 3.6 e	11.2 ± 0.6 b
	N1M_2	14.6 ± 0.2 bc	76.2 ± 4.0 d	11.1 ± 0.6 b
	N2M_1	16.0 ± 0.8 ab	85.6 ± 1.0 c	13.7 ± 0.2 ab
	N2M_2	16.5 ± 1.1 ab	92.5 ± 4.2 b	15.3 ± 0.7 a
	N3M_1	12.8 ± 1.0 c	94.3 ± 3.1 ab	12.1 ± 0.4 b
	N3M_2	13.8 ± 0.5 c	99.5 ± 2.1 a	13.7 ± 0.3 ab
F value	N	9.92 **	143.38 **	78.43 **
	M	0.01 ns	10.36 **	12.36 **
	N*M	0.95 ns	1.21 ns	4.68 *

Table 4. *Cont.*

Year	Treatment	Sugar Content (%)	Taproot Yield (t/ha)	Sugar Yield (t/ha)
2017	CK	17.1 ± 1.1 abc	65.9 ± 2.5 d	11.3 ± 0.4 f
	$N1M_1$	16.3 ± 0.7 abc	77.9 ± 5.9 cd	12.7 ± 1.1 ef
	$N1M_2$	17.5 ± 0.5 a	80.9 ± 2.5 c	14.2 ± 0.4 de
	$N1M_3$	14.4 ± 0.3d	78.2 ± 3.7 cd	11.3 ± 0.5 f
	$N2M_1$	16.4 ± 0.4 abc	109.0 ± 12.2 ab	17.9 ± 2 ab
	$N2M_2$	17.3 ± 1.7 ab	114.5 ± 2.6 a	19.8 ± 0.4 a
	$N2M_3$	15.3 ± 1.2 cd	108.3 ± 6.2 ab	16.6 ± 0.9 bc
	$N3M_1$	16.0 ± 1.4 abcd	102.6 ± 2.9 ab	16.4 ± 0.5 bc
	$N3M_2$	16.5 ± 0.3 abc	103.1 ± 12.3 ab	17.0 ± 2.1 bc
	$N3M_3$	15.6 ± 1.1 bcd	96.6 ± 10.7 b	15.1 ± 1.7 cd
F value	N	1.99 ns	82.58 **	74.61 **
	M	6.62 **	1.01 ns	10.62 **
	N*M	1.31 ns	0.28 ns	1.42 ns
2018	CK	15.9 ± 0.7 b	60.7 ± 4.4 d	9.6 ± 0.7 e
	$N1M_1$	16.2 ± 0.8 ab	71.4 ± 3.6 c	11.6 ± 0.6 d
	$N1M_2$	14.2 ± 1.1 b	72.6 ± 2.2 c	10.3 ± 0.3 de
	$N1M_3$	15.1 ± 1.3 b	68.6 ± 4.7 cd	10.4 ± 0.7 de
	$N2M_1$	15.4 ± 1.1 b	90.5 ± 7.3 b	13.9 ± 1.1 bc
	$N2M_2$	16.8 ± 1.3 a	98.5 ± 6.1 ab	16.5 ± 1.0 a
	$N2M_3$	14.2 ± 0.9 b	92.4 ± 8.1 b	13.1 ± 1.1 c
	$N3M_1$	14.5 ± 0.8 b	96.3 ± 6.8 ab	14.0 ± 1.2 bc
	$N3M_2$	15.2 ± 0.2 b	100.0 ± 5.3 a	15.2 ± 0.8 ab
	$N3M_3$	16.0 ± 0.2 ab	94.4 ± 2.0 b	15.1 ± 0.3 ab
F value	N	1.27 ns	101.49 **	95.22 **
	M	0.27 ns	1.94 ns	3.84 *
	N*M	4.04 **	0.44 ns	5.22 **

Different lowercase letters indicate a significant difference at $p < 0.05$ according to the Duncan test. *, $p < 0.05$; **, $p < 0.01$; ns, $p > 0.05$.

3.8. Correlation between Yield, Sugar Content, and aNUE of Sugar Beet at Harvest Time, and Leaf Growth and Senescence under Different N Fertilizer Management

The sugar content (SC) of sugar beet was positively correlated with the leaf senescence rate (LSR) ($p > 0.05$), and negatively correlated with LAD and LAI in 2016. In addition, in the three years, TY and SY were positively correlated with LAD and LAI ($p < 0.05$), and negatively correlated with LSR ($p < 0.05$) (Figure 7).

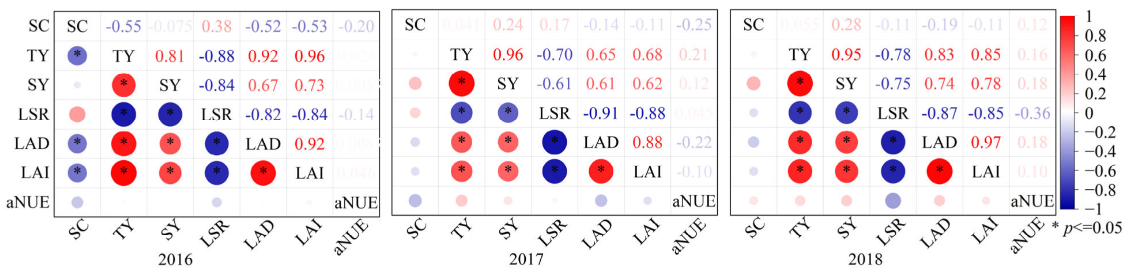

Figure 7. Correlation analysis between leaf growth parameters (leaf area index (LAI), leaf area duration (LAD), and leaf senescence rate (LSR)), yield parameters (sugar content (SC), sugar yield (SY), and taproot yield (TY)), and agronomic N use efficiency (aNUE) of sugar beet under different N application rates (CK, N1, N2, and N3) and N application methods (M_1, M_2, and M_3) in 2016–2018.

4. Discussion

Nitrogen fertilizer application is a routine measure to ensure high sugar beet yields. Unlike other crops such as wheat and maize, N fertilizer management for sugar beet should promote the transfer of dry matter to the taproot [12,26]. This study found that N application, especially N3, increased the growth rate of sugar beet shoots and taproots, thus increasing the DMA (Figures 1 and 2). It was found that postponing the application of a portion of the N fertilizer until the taproot expansion stage (M_2), or even a later stage (M_3), further increased the growth rate and DMA of sugar beets compared with only applying N at the canopy rapid growth stage (M_1) (Figure 1). This is due to the fact that N is one of the important components of the photosynthetic pigments and enzymes involved in N metabolism [7,27]. In the early stage of sugar beet growth, the sugar beet plants are small and the growth is slow. Too much available N in the soil (too much N fertilizer) cannot be fully absorbed by the plants to promote plant growth [17,28]. Conversely, the applied N may be leached into deep soils by irrigation water and rainfall, or discharged into the atmosphere as NH_3 and N_2O through nitrification and denitrification. This not only increases the risk of environmental pollution, but also reduces N use efficiency [21]. Therefore, in this study, postponing the application of a portion of N fertilizer (30% of the total N fertilizer) to the taproot expansion stage could increase the daily DMA rate, prolong the DMA time, and promote the partition of dry matter to taproots (Figure 3).

In this study, a high N application rate (N3) increased the LAI of sugar beets compared with the CK treatment. Moreover, postponing the application of a portion of the N fertilizer to the taproot expansion stage (M_2) could not only increase the LAI and LAD (Figure 4), but also reduce the LSR. This delays the premature senescence of leaves, so that sugar beet still has a large leaf area for photosynthesis and a high leaf area duration in the late growth stage, which ultimately increases the dry matter production and the dry matter transferred to taproots. The results of correlation analysis also showed that there was a significant positive correlation between LAI/LAD and taproot/sugar yield in the three years. On the contrary, there was a significant negative correlation between leaf senescence rate and taproot/sugar yield. This further suggests that the postponed application of some N fertilizer to the taproot expansion stage could reduce the leaf senescence rate, which can increase yield [29].

In this study, although N application significantly increased taproot yield compared with CK treatment, there was no difference in taproot yield between 225 kg N ha^{-1} (N3) and 150 kg N ha^{-1} (N2) treatment. This suggests that the overapplication of N fertilizer is not appropriate, which is consistent with other studies [26,30,31]. The results of this study also showed that the N application rate and N application method had a significant effect on the aNUE of sugar beet (Figure 5). This is consistent with the results of previous studies on maize [32,33], that is, appropriately reducing the N application rate in the early growth stage of maize and increasing the N application rate in the middle and late growth stages are conducive to improving the N use efficiency. In addition, this study found that the sugar content was not significantly increased after N application and the postponed application of some N fertilizer, and it even decreased to varying degrees (Table 2). This indicates that the increase in sugar yield is not due to the increase in sugar content, but due to the increase in taproot yield. Wu et al. [34] reported that increasing the availability of N in the soil stimulated the "foraging" of the taproots; i.e., sugar beets might grow more fibrous roots to absorb water and N from the soil [35]. This may also be one of the reasons for the reduced sugar content in this study. In addition, the accumulation of sucrose in taproots is also related to the transport of sucrose from shoot to taproot and the sugar metabolism in taproot, but there is insufficient evidence to reveal the response of these processes to N fertilizer management. Therefore, in future research, the response of sucrose transport and sucrose metabolism under different N fertilizer management strategies will be explored.

5. Conclusions

Nitrogen application (N1, N2, and N3) significantly increased the dry matter accumulation in the shoot and taproot of sugar beets at harvest time compared with the treatment without N application. Applying 70% and 30% of the total N fertilizer in the canopy rapid growth stage and the taproot expansion stage, respectively, met the N demand in the late growth stage of sugar beet. At the same time, it increased the leaf area index and leaf area duration and delayed leaf senescence. This increased the N accumulation of plants, and promoted the transport of photosynthetic products to the taproot, which was conducive to increasing the sugar beet yield and agronomic N use efficiency. This study clarified that the application of 70% and 30% of 150 kg N ha^{-1} at the canopy rapid growth stage and taproot expansion stage of sugar beet could improve the yield and agronomic nitrogen use efficiency of drip-irrigated sugar beet in arid areas.

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Data Availability Statement: Raw data can be provided upon request.

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