agronomy

Article

Optimizing N Application for Forage Sorghum to Maximize Yield, Quality, and N Use Efficiency While Reducing Environmental Costs

Wei Gao [1,2], Na Shou [1,2], Congze Jiang [1,2], Renshi Ma [1,2] and Xianlong Yang [1,2,*]

[1] College of Pastoral Agriculture Science and Technology, Lanzhou University, Lanzhou 730020, China
[2] National Field Scientific Observation and Research Station of Grassland Agro-Ecosystems in Gansu Qingyang, Lanzhou University, Lanzhou 730020, China
* Correspondence: yangxianl@lzu.edu.cn

Abstract: Investigating the responses of forage crop yield, quality, and nitrogen (N) use efficiency to different N application rates is beneficial for guiding proper N fertilization regimes and for reducing reactive N environmental pollution. A field experiment was conducted to investigate the effects of different N application rates on above-ground dry matter yield, forage quality, crop N uptake, N use efficiency (NUE), and ecosystem economic benefits (EEBs) of forage sorghum cultivated on the Longdong Loess Plateau in 2019 and 2020. Five N application rates were tested, namely 0, 80, 160, 240, and 320 kg·ha^{-1} (referred to as N_0, N_{80}, N_{160}, N_{240}, and N_{320}, respectively). The maximum above-ground dry matter yield (22.3 t·ha^{-1} in 2019 and 18.0 t·ha^{-1} in 2020) was obtained at an N application of 160 kg·ha^{-1}. Forage sorghum crude protein (CP) content increased significantly with increasing N application rates (the CP content at N_{320} was 7.4% and 8.6% in 2019 and 2020, respectively). In contrast, neutral detergent fiber (NDF) and acid detergent fiber (ADF) were only affected by high N application rates (NDF and ADF were significantly higher in N_{320} compared with N_0 and N_{90}). The relative feed value (RFV) was significantly higher in N_0 compared with N_{320}. Crop N uptake was significantly higher in N_{160} compared with N_0 (25.7% increase to 249.4 kg·ha^{-1} in 2019 and 40.5% increase to 247.4 kg·ha^{-1} in 2020, respectively). NUE decreased linearly as N rates increased, but NO_3^-–N residue (0–200 cm), reactive N loss (Nr loss), and greenhouse gas (GHG) emissions increased. Private profitability and EEB were the largest at N_{160} (private profitability at N_{160} was 514.2 USD·ha^{-1}, and EEB at N_{160} was 392.7 USD·ha^{-1}). Above-ground yield and optimum forage quality must be maximized, while simultaneously safeguarding farmer income and reducing environmental pollution from N fertilizers. Therefore, the optimum N application rate for forage sorghum cultivation in the dry areas of the Loess Plateau is recommended at 160 kg·ha^{-1}.

Keywords: forage sorghum; dry matter yield; crop N uptake; N use efficiency; ecosystem economic benefits

check for updates

Citation: Gao, W.; Shou, N.; Jiang, C.; Ma, R.; Yang, X. Optimizing N Application for Forage Sorghum to Maximize Yield, Quality, and N Use Efficiency While Reducing Environmental Costs. *Agronomy* **2022**, *12*, 2969. https://doi.org/10.3390/agronomy12122969

Academic Editor: Alfonso S. Frenda

Received: 27 October 2022
Accepted: 23 November 2022
Published: 25 November 2022

1. Introduction

Sorghum is the fifth largest food crop in the world. Global sorghum production in 2021 was 6216.7 × 10^4 t, of which about 44% was used as forage, while the Americas and Asia are the major producing regions accounting for 83.8% and 10.9% of global forage sorghum production during 2000–2014, respectively (data source: official website of Food and Agriculture Organization of the United Nations). The forage sorghum industry fulfills two primary functions, namely production and ecology. On the one hand, forage sorghum is an important food source for livestock, and its various nutrients and crude fibers contained are irreplaceable by other feeds and grains. On the other hand, the rotation of sorghum with legumes (e.g., soybean) effectively improves soil fertility and nitrogen (N) stocks and aids in soil and water conservation [1]. Therefore, ensuring that enough forage is available is the key to the high-quality development of the livestock industry. Human living standards are continuously improving as the economy develops, and the demand for animal products, such as meat, eggs, and milk is increasing annually. For example, the production of meat, eggs, and milk in China during 2021 was 66.2% higher than 20 years before (data source: official website of National Bureau of Statistics of China). However, the shortage of high-quality forage has become a limiting factor for the sustainable management of China's livestock industry. For example, domestic soybean production in 2020 was 1.96×10^7 t, while the amount of imported soybeans (1.00×10^8 t) was five times higher than domestic production (data source: official website of National Bureau of Statistics of China). Forage sorghum has increasingly been considered as the ideal feedstock, since it produces a high biomass and is well-adapted to growth conditions with high soil salinity and low precipitation [2]. Forage sorghum roots are able to access water in soils as deep as 270 cm [3]. This can increase yields by up to 540% compared with maize during severe drought conditions [4]. Forage sorghum can therefore be used effectively in arid and semi-arid areas. Forage sorghum also has a high nutritional value and its consumption thus leads to better livestock performance [5] Miron et al. [6] reported that feeding sorghum to cows increased their milk fat content by 9.2% compared with cows raised on corn. As a result, an increased usage of forage sorghum can significantly reduce the feed shortfall.

Cultivation practices such as fertilization and irrigation are essential to improve forage biomass and quality, as well as nutrient use efficiency. N is the primary nutrient that determines plant productivity [7]. A properly applied N amount can improve crop light energy usage, thus affecting photosynthetic product accumulation. The optimal amount of N required for crops depends on the region and variety. Sawargaonkar et al. [3] reported the optimum N application rate for forage sorghum to be 90 $kg \cdot ha^{-1}$. Marsalis et al. [8] indicated that maximum dry matter yield (24.6 $t \cdot ha^{-1}$) can be achieved with an N application rate of 218 $kg \cdot ha^{-1}$. However, excessive N fertilizer application can limit crop yield and reduce N use efficiency (NUE) [9,10]. Most studies have indicated that a proper N application rate effectively increases the crude protein (CP) content of forage sorghum. Nematpour et al. [11] reported that an N application rate of 112.5 $kg \cdot ha^{-1}$ increased the CP content of sorghum by 48.8% compared with no N application. N application and its effects on neutral detergent fiber (NDF), acid detergent fiber (ADF), and crude ash (ASH) remain controversial. Specifically, the NDF and ADF content of sorghum treated with N can be reduced by up to 6.0% and 5.8%, respectively, compared with no N application [12]; however, Sher et al. [13] indicated the opposite, namely that N application increases sorghum ADF and NDF content. Most studies have concluded that sorghum ADF, NDF, and ASH content are influenced by genes rather than N application [8,14]. Therefore, further research is needed to investigate how N application affects forage sorghum quality.

Currently, excessive N application in China accounts for 20% of the cultivated area, and national N fertilizer application levels have been increasing. Projections indicate that this will continue until 2050 [15]. Excessive N application results in significant soil NO_3^-–N accumulation [16] and thus decreased NUE. Increased soil N levels that remain unavailable to crops can lead to environmental problems such as soil acidification, groundwater contamination, and greenhouse gas (GHG) emissions [17–19]. Currently, no research has been conducted to the environmental effects of reactive N (Nr) losses and GHG emissions from N fertilization during forage sorghum growth.

The Longdong Loess Plateau is an important area for livestock development in Gansu Province, and forage sorghum is kind of ideal fodder crops for cultivation in this area due to its high yield, quality, and strong stress resistances. Currently, the appropriate N fertilizer rates to maximize crop yield and forage quality while minimizing environmental costs in this area have not been determined. We thus conducted a two-year continuous field experiment to determine how different N application rates affect forage sorghum agronomic parameters (above-ground dry matter yield, forage quality, and N uptake), NUE, environmental impacts (Nr losses, GHG emissions), and ecosystem economic benefits (EEBs). These results are essential for identifying optimal N management strategies and to promote sustainable forage sorghum production with low environmental costs.

2. Materials and Methods

2.1. Site Description

The experiment was conducted during 2019 and 2020 at the Loess Plateau Research Station of Lanzhou University (35°39′ N, 107°51′ E) in Qingyang city, Gansu province, China. The experimental site is located in a rainfed agriculture region. According to meteorological data (2001–2020), the mean precipitation and air temperature in this area is 579.1 mm and 10.1 °C, respectively. Monthly precipitation and air temperature for 2019 and 2020 are provided in Figure 1, and total precipitation during the forage sorghum growing season was 590.1 and 472.1 mm during 2019 and 2020, respectively. The 0–60 cm soil layer characteristics were as follows: bulk density 1.36 g·cm^{-3}, organic matter content 15.30 g·kg^{-1}, total soil N 0.88 g·kg^{-1}, NO_3^-–N 49.53 mg·kg^{-1}, available P (Olsen-P) 21.53 mg·kg^{-1}, and pH 8.2.

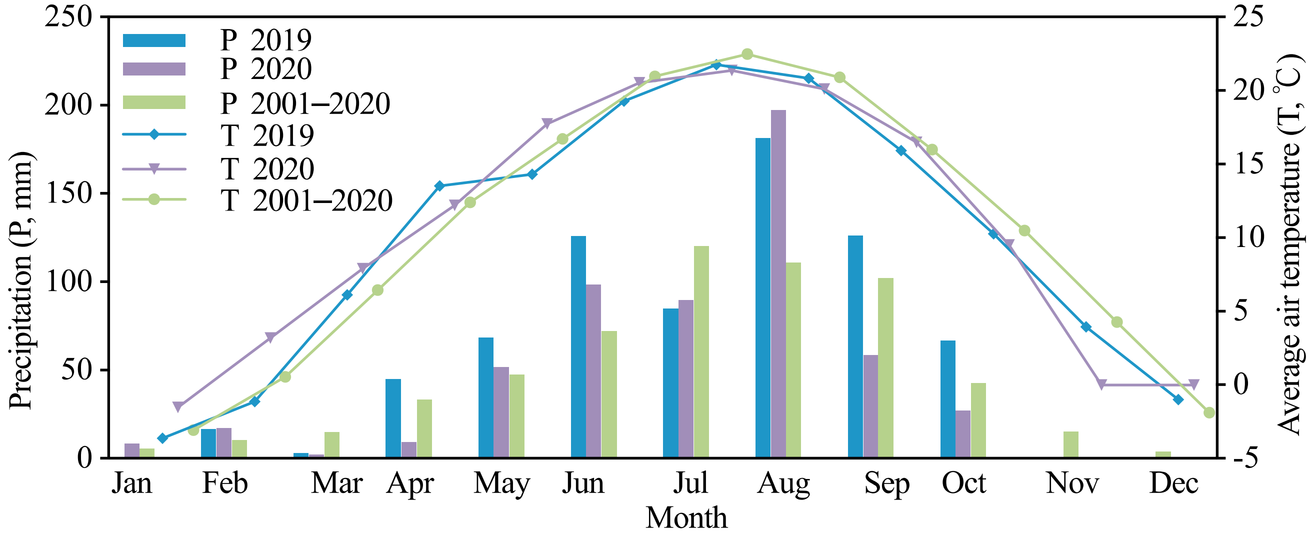

Figure 1. Distribution of monthly precipitation and average air temperature in 2019, 2020, and the long terms (2001−2020) in the study area.

2.2. Experimental Design and Management

The experiment was conducted in a randomized complete block design with five N rates of 0, 80, 160, 240, and 320 kg·ha^{-1} (expressed as N_0, N_{80}, N_{160}, N_{240}, and N_{320}). Each treatment was conducted in triplicate. Urea (N, 46%) was applied in two applications, with 30% of the N fertilizer applied as a basal fertilizer and 70% applied at the jointing stage. Superphosphate (P_2O_5, 16%) and potassium sulfate (K_2O, 51%) were used as basal fertilizer for all plots with a single application of 120 kg·ha^{-1} P_2O_5 and 150 kg·ha^{-1} K_2O, respectively.

The forage sorghum cultivar 'F10' was used. 'F10' is a promising variety with salinity and drought tolerance. The experimental plot area was 24 m^2 (4 m × 6 m). The planting density was 67,500 plants·ha^{-1} with a row spacing of 0.5 m and a plant spacing of 0.3 m. In 2019, forage sorghum was sown on 26 May and harvested on 20 October. In 2020, sorghum was sown on 19 April and harvested on 18 September. In both years, ploughing was performed after crop harvest. The predecessor crop to sorghum in 2018 were winter wheat and the two years of experiments were conducted in the same plot. No irrigation or pesticides were used during the experimental period.

2.3. Measurements and Calculations

2.3.1. Crop Sample Collection and Measurement

Plant height, stem diameter, NDVI, and LAI were all measured approximately every 15 days. Plant height and stem diameter were measured on five selected representative plants in each plot using a straightedge and vernier caliper. Plant NDVI and LAI were measured using a Green Seeker handheld optical sensing instrument (DELTRAN, Deland, FL, USA) and LAI-2000 (LI-COR, Lincoln, NE, USA). Five plants were randomly selected from each plot at the jointing, heading, flowering, filling, and harvesting stage, and the five plants were subdivided into stems, leaves, and ears, cut into lengths of 3–5 cm and weighed respectively. They were oven-dried at 105 °C for 30 min, then at 75 °C until a constant weight was obtained, and finally weighed again. The forage sorghum was harvested at the milk stage. Fresh yield was measured for each plot and above-ground dry matter yield was obtained after measuring water content. The moisture content of the above-ground portion of forage sorghum at the harvest stage in 2019 and 2020 was 69.9% and 69.4%, respectively. Dry samples were crushed and passed through a 0.425 mm mesh, and N concentration, neutral NDF, ADF, and ASH were determined using the Kjeldahl, Van Soest's, and high-temperature scorching methods [20], respectively. One mixed sample was analyzed for each plot.

Quality indices for animal feed, including dry matter intake (DMI), dry matter digestibility (DMD), and relative feed value (RFV) were calculated using the following formulas [21,22]:

$$\text{DMI }(\%) = \frac{120}{\text{NDF}} \tag{1}$$

$$\text{DMD }(\%) = 88.9 - 0.779 \times \text{ADF} \tag{2}$$

$$\text{RFV }(\%) = \text{DMD} \times \frac{\text{DMI}}{1.29} \tag{3}$$

2.3.2. Evaluation of NUE

The N recovery rate (RE) and partial-factor productivity of applied N (PFP) were used to evaluate NUE, and these indicators were calculated as follows [23]:

$$\text{RE }(\%) = \left(\frac{U_N - U_0}{N}\right) \times 100\% \tag{4}$$

$$\text{PFP }\left(\text{kg}\cdot\text{kg}^{-1}\right) = \frac{Y_N}{N} \tag{5}$$

where U_N is N uptake (kg·ha^{-1}) with N fertilizer, U_0 is N uptake (kg·ha^{-1}) without N fertilizer, Y_N is above-ground dry matter yield (kg·ha^{-1}) with N fertilizer, and N is N fertilizer input (kg N·ha^{-1}).

2.3.3. Soil Sample Collection and Measurement

Soil samples were collected between a depth of 0–200 cm at 20 cm intervals on pre-sowing dates, as well as three growth stages (jointing, flowering, and harvesting). Soil samples were collected, and sealed in plastic bags, from two randomly selected locations per plot and stored in a refrigerator until required for analysis. Soil NO_3^-–N content was determined using an automatic discontinuous chemical analyzer (Smart-Chem 450, French). The NO_3^-–N residue (NR) in each soil layer was calculated as follows [24]:

$$\text{NR}\left(\text{kg N}\cdot\text{ha}^{-1}\right) = \text{NC}_i \times \text{BD}_i \times \text{SD} \times 0.1 \tag{6}$$

where NC_i is the soil NO_3^-–N content of the ith soil layer (mg·kg^{-1}), BD_i is the soil bulk density of the ith soil layer (g·cm^{-3}), SD is soil depth (cm), and 0.1 is a conversion factor.

2.3.4. Reactive N Loss and Footprint Calculations

Nr loss and NF were calculated using the following equations [25]:

$$\text{Nr loss }\left(\text{kg N}\cdot\text{ha}^{-1}\right) = \sum_{i=1}^{m} \text{Rate}_i \times F_i + N_2O_{direct}\text{–N} + NO_3\text{–N} + NH_3\text{–N} \tag{7}$$

$$\text{NF}\left(\text{kg N}\cdot\text{t}^{-1}\right) = \text{Nr loss}/\text{Y}_\text{N} \tag{8}$$

where i represents agricultural input (N fertilizer and other inputs), Rate_i is the agricultural materials input application rate, and F_i represents the Nr emission factor during the production and transportation of agricultural products. Rate_i and F_i values for this study are listed in Tables 1 and A1 [26–28]. Y_N represents the total above-ground dry matter yield with the application of N fertilizer ($t\cdot ha^{-1}$). N_2O_{direct}–N, NO_3–N, and NH_3–N are Nr losses due to N_2O emissions, $NO_3{}^-$ leaching, and NH_3 volatilization during N fertilizer application. Nr losses, represented by N_2O_{direct}–N, NO_3–N, and NH_3–N from N fertilizer, were calculated according to fitted models based on previously published reports (Figure A1) [29–38]. The models were:

$$\text{N}_2\text{O}_\text{driect}\text{–N}\left(\text{kg N}\cdot\text{ha}^{-1}\right) = 0.0195 \times \text{N} + 0.3095 \tag{9}$$

$$\text{NO}_3\text{–N}\left(\text{kg N}\cdot\text{ha}^{-1}\right) = 0.0497 \times \text{N} + 1.8391 \tag{10}$$

$$\text{NH}_3\text{–N}\left(\text{kg N}\cdot\text{ha}^{-1}\right) = 5.0215 \times e^{(0.0091\times \text{N})} \tag{11}$$

where N is the N application rate ($kg\ N\cdot ha^{-1}$).

Table 1. Application rate of agricultural inputs in the forage sorghum production system.

Agricultural Materials	**N Fertilizer ($\mathbf{kg\ N\cdot ha^{-1}}$)**	**P Fertilizer ($\mathbf{kg\ P_2O_5\cdot ha^{-1}}$)**	**K Fertilizer ($\mathbf{kg\ K_2O\cdot ha^{-1}}$)**
Rate	0/80/160/240/320	120	150

2.3.5. GHG Emissions and CF Calculations

GHG emissions and C footprints (CF) were calculated using the following equations [25]:

$$\text{GHG}\left(\text{kg CO}_2\text{ eq}\cdot\text{ha}^{-1}\right) = \sum_{i=1}^{m} \text{Rate}_i \times \text{G}_i + 265 \times \text{N}_2\text{O}_\text{total}\text{–N} \times 44/28 \tag{12}$$

$$\text{N}_2\text{O}_\text{total}\text{–N}\left(\text{kg N}\cdot\text{ha}^{-1}\right) = \text{N}_2\text{O}_\text{driect}\text{–N} + 1\% \times \text{NH}_3\text{–N} + 2.5\% \times \text{NO}_3\text{–N} \tag{13}$$

$$\text{CF}\left(\text{kg CO}_2\text{ eq}\cdot\text{t}^{-1}\right) = \frac{\text{GHG}}{\text{Y}_\text{N}} \tag{14}$$

where i represents agricultural input (N fertilizer and other inputs), Rate_i is the application rate of agricultural materials input, and G_i represents the GHG emission factor during the production and transportation of agricultural products. Rate_i and G_i values used in this study are listed in Tables 1 and A1 [26–28]. The global warming potential of N_2O is 265 times that of CO_2 on a mass basis [39]. The factor used to convert N_2O–N to CO_2 was 44/28. N_2O_{total}–N represents the total N_2O–N loss from direct and indirect pathways. The indirect N_2O–N emissions were the sum of 1% NH_3–N and 2.5% NO_3–N [40]. Y_N represents total above-ground dry matter yield with the application of N fertilizer ($t\cdot ha^{-1}$).

2.3.6. N Fertilizer-Derived Ecosystem Economic Benefits

Accounting for ecosystem and human health costs, the estimated N-derived yield benefits (B_Y), private profitability, and EEB were calculated using the following equations [25]:

$$\text{B}_\text{Y}\left(\$\cdot\text{ha}^{-1}\right) = (\text{Y}_\text{N}\text{–Y}_0) \times \text{S}_\text{Price} \tag{15}$$

$$\text{Private profitability}\left(\$\cdot\text{ha}^{-1}\right) = \text{B}_\text{Y}\text{–N}_{\cos t}\text{–L}_{\cos t} \tag{16}$$

$$\text{EEB}\left(\$\cdot\text{ha}^{-1}\right) = \text{B}_\text{Y}\text{–N}_{\cos t}\text{–L}_{\cos t}\text{–E}_{\cos t}\text{–H}_{\cos t} \tag{17}$$

where Y_N represents total above-ground dry matter yield with the application of N fertilizer, and Y_0 represents the total above-ground dry matter yield without N fertilizer. S_{Price} was 0.25 USD·kg^{-1} and represents the forage sorghum price for silage [25]. The N_{cost} and L_{cost} are the N fertilizer and labor costs associated with N fertilizer application. They were calculated by multiplying the amount of N or labor applied by the corresponding price (N fertilizer = 0.64 USD·kg^{-1}; single-person labor cost = 1.47 USD·h^{-1}; data source: http://zdscxx.moa.gov.cn/month/nycsc3/zlsc317#nycsc3/ (accessed on 20 August 2022). E_{cost} represents ecosystem damage costs caused by Nr losses, while H_{cost} represents the human health costs caused by various Nr losses resulting from N fertilizer application. These were calculated as follows [41]:

$$E_{cost} = C_{GHG} + C_{eu} + C_{acid} = (CO_2 \times 0.0204) + (1.12 \times NO_3\text{–}N + 0.24 \times NH_3\text{–}N + 0.0018 \times N) + (1.87 \times NH_3\text{–}N + 0.021 \times N) \quad (18)$$

$$H_{cost} = (0.30 \times N_2O_{total}\text{–}N + 0.20 \times NO_3\text{–}N + 3.30 \times NH_3\text{–}N \quad (19)$$

where C_{GHG}, C_{eu}, and C_{acid} represent GHG emission, water eutrophication, and soil acidification damage costs [42]. CO_2 is the total GHG emissions from N fertilizer production, transportation, and application. The CO_2 market price was 0.0204 USD·kg^{-1} [43]. The eutrophication impact restoration cost for NO_3–N and NH_3–N was 1.12 and 0.24 USD·kg^{-1}, respectively [44]. The soil acidification damage restoration cost for NH_3–N was 1.87 USD·kg^{-1} [44,45]. The costs of eutrophication and soil acidification damage per kg of N fertilizer were 0.0018 and 0.021 USD·kg^{-1} [45], respectively. The human health cost per unit of N_2O_{total}–N, NO_3–N, and NH_3–N were 0.30, 0.20, and 3.30 USD·kg^{-1} [46], respectively.

2.4. Statistical Analysis

Agronomic traits, forage quality, dry matter yield, crop N content, crop N uptake, NUE, NO_3^-–N accumulation, Nr loss, CF, and NF were compared using Analysis of Variance (ANOVA) and the Duncan method (p = 0.05) in SPSS (26.0, SPSS Inc., Chicago, IL, USA). The data in the graphs are expressed as mean ± standard error. GraphPad Prism (9.1.1, GraphPad Software, Inc., San Diego, CA, USA) was used to generate the graphs.

3. Results

3.1. Dynamics of Plant Height, Stem Diameter, LAI, NDVI, and Dry Matter Accumulation

During the forage sorghum growth period, plant height, stem diameter, LAI, and NDVI generally increased at first, whereafter they remained either stable or decreased (Figure 2). In 2019, forage sorghum plant height, stem diameter, and NDVI were not significantly different between treatments ($p > 0.05$). In 2020, plant height, stem diameter, and NDVI at N_{160} were 3.3 m, 2.3 cm, and 0.8, respectively, which were 7.7%, 4.7%, and 9.3% significantly higher compared with N_0 ($p < 0.05$), respectively. During the two-year harvest stages, LAI peaked in N_{160} with values of 2.7 in 2019 and 2.4 in 2020, respectively, which were 5.1% and 12.3% higher compared with N_0, respectively ($p < 0.05$).

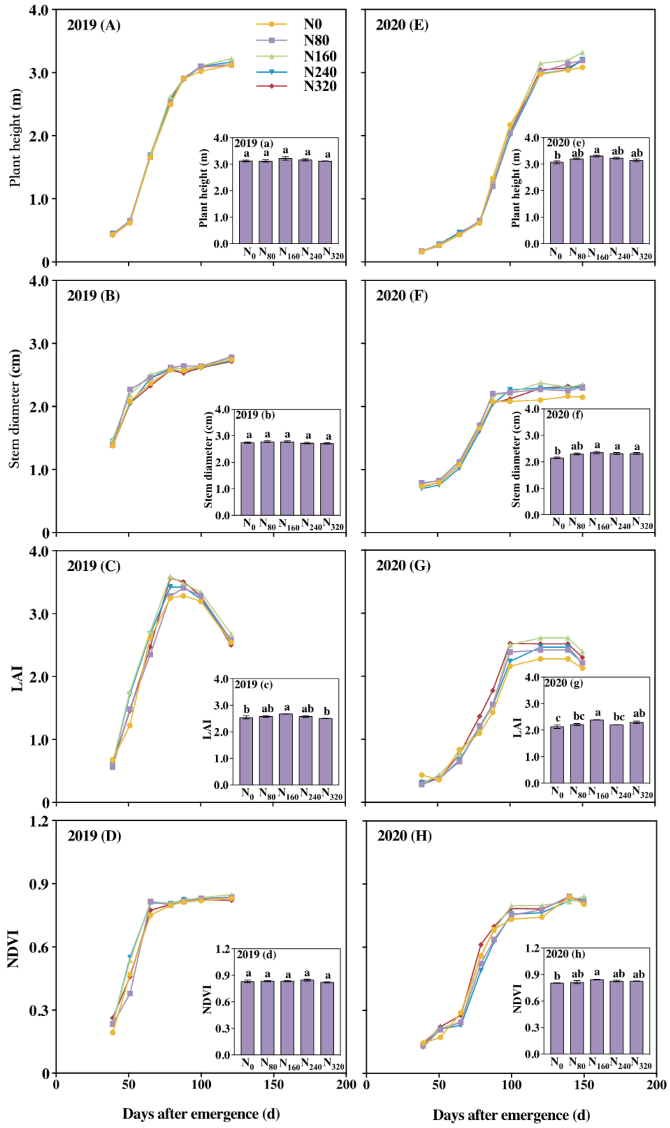

Figure 2. Dynamics of mean plant height (**A**,**E**), stem diameter (**B**,**F**), LAI (**C**,**G**), and NDVI (**D**,**H**) of forage sorghum and their mean values at the harvest stage under different N application rates in 2019 and 2020 (**A**–**H**). Different lowercase letters indicate significant differences at $p < 0.05$ among the different N treatments.

Above-ground total dry matter accumulation (TDMA) either gradually increased, or first increased and then decreased, with increasing N application rates under the different growth stages (Figure 3). At the heading, flowering, and filling stages in 2019, above-ground TDMA values in N_{160} were 8.6, 11.8, and 18.6 t·ha^{-1}, respectively, which were 113.6%, 28.8%, and 14.0% significantly higher compared with N_0 ($p < 0.05$). At the harvest stage in 2019, above-ground TDMA was the highest in N_{160} (22.3 t·ha^{-1}), but it did not differ significantly from the other N application treatments ($p > 0.05$). At the heading and flowering stages in 2020, above-ground TDMA values in N_{320} increased significantly by 65.3% and 79.8%, respectively, compared with N_0 ($p < 0.05$). Moreover, N_{160} had the highest above-ground TDMA (18.0 t·ha^{-1}) at the harvest stage in 2020, which was 23.8% significantly higher compared with N_0 (14.5 t·ha^{-1}) ($p < 0.05$). During the harvest stage in 2019 and 2020, stem and ear dry matter accumulation (DMA) was highest in N_{160} (15.6 and 13.2 t·ha^{-1} for stems; 3.3 and 1.79 t·ha^{-1} for ears). However, leaf DMA did not differ significantly among all N application treatments during the two years ($p > 0.05$).

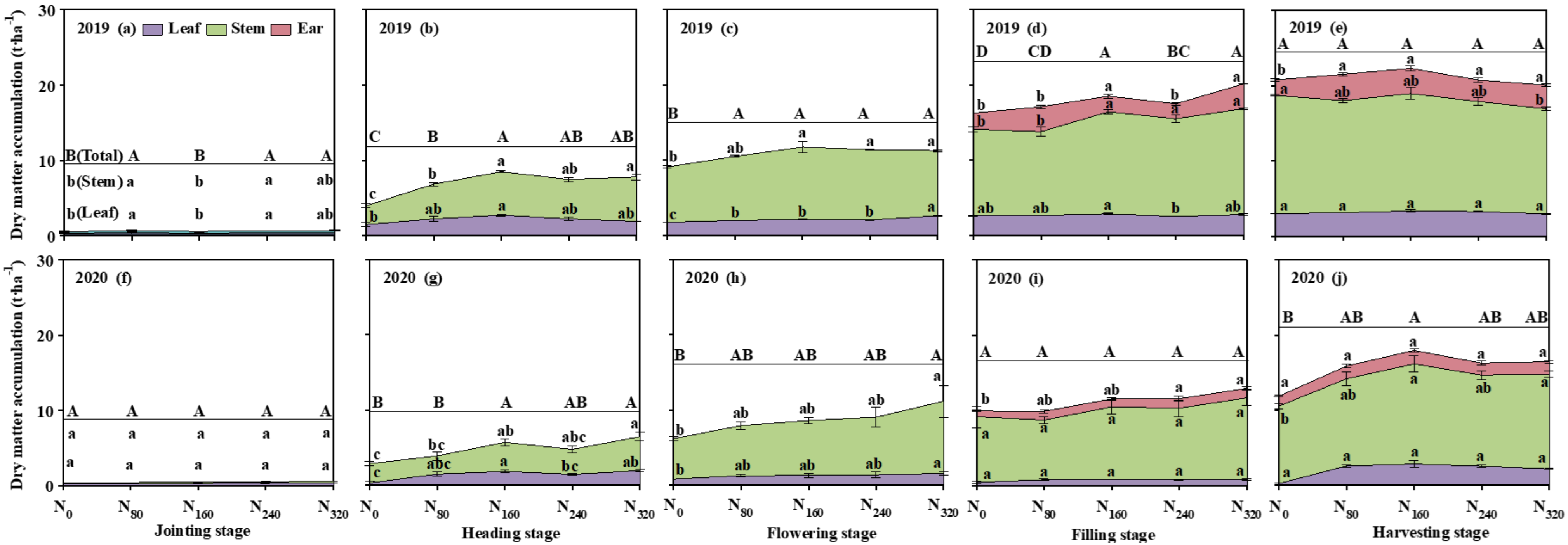

Figure 3. Dynamics of dry matter accumulation of leaf, stem, and ear in forage sorghum under different N application rates in 2019 (**a**−**e**) and 2020 (**f**−**j**). The different lowercase letters in the same parts (leaf, stem, and ear) represent significant difference at $p < 0.05$ among the different N treatments. Different capital letters represent significant differences at $p < 0.05$ in the total above−ground parts of dry matter accumulation among the different N treatments.

3.2. NDF, ADF, ASH, CP, and RFV

At the respective harvest stages during the two years, NDF was the highest in N_{320} (58.0% in 2019 and 59.7% in 2020) and significantly higher compared with N_0 and N_{80} (Table 2; $p < 0.05$). ADF was also the highest in N_{320}, which was 12.6% and 13.5% significantly higher in 2019 and 2020 compared with N_0 ($p < 0.05$). N application did not significantly affect ASH in either of the years ($p > 0.05$). At the harvest stage in 2019 and 2020, CP values did not differ significantly between N_{160}, N_{240}, and N_{320} ($p > 0.05$), but they were significantly higher compared with N_0 ($p < 0.05$). During the two-year experiment, there were no significant differences in DMI, DDM, and RFV at N_0, N_{80}, N_{160}, and N_{240} ($p > 0.05$). In 2019 and 2020, DMI, DDM, and RFV values were the lowest in N_{320}, and were all significantly lower compared with the other treatments (N_0, N_{80}, N_{160}, and N_{240}; $p > 0.05$).

Table 2. The NDF, ADF, ASH, CP, DMI, DDM, and RFV of forage sorghum at the harvest stage under different N application rates in 2019 and 2020.

Years	Treatments	NDF (%)	ADF (%)	ASH (%)	CP (%)	DMI (%)	DDM (%)	RFV (%)
2019	N_0	51.5 ± 2.2 b	29.6 ± 2.5 b	4.8 ± 0.3 a	6.0 ± 0.3 c	2.3 ± 0.1 a	65.9 ± 2.0 a	119.6 ± 8.3 a
	N_{80}	51.8 ± 1.0 b	29.3 ± 1.4 b	4.8 ± 0.4 a	6.9 ± 0.3 b	2.3 ± 0.1 a	66.1 ± 1.1 a	119.0 ± 4.3 a
	N_{160}	55.5 ± 3.1 ab	28.1 ± 2.1 b	4.7 ± 0.2 a	7.0 ± 0.1 ab	2.2 ± 0.1 ab	67.0 ± 1.6 a	113.0 ± 8.0 ab
	N_{240}	55.2 ± 1.5 ab	30.6 ± 1.5 ab	4.9 ± 0.9 a	7.3 ± 0.1 ab	2.2 ± 0.1 ab	65.2 ± 1.1 ab	110.2 ± 5.0 ab
	N_{320}	58.0 ± 3.1 a	33.3 ± 2.2 a	4.8 ± 0.3 a	7.4 ± 0.2 a	2.1 ± 0.1 b	63.0 ± 1.7 b	101.8 ± 8.4 b
2020	N_0	53.9 ± 0.44 b	28.5 ± 0.1 b	5.7 ± 0.2 a	7.8 ± 0.2 b	2.2 ± 0.1 a	66.7 ± 0.1 a	115.0 ± 1.0 a
	N_{80}	56.3 ± 1.6 b	30.1 ± 1.5 b	6.0 ± 0.4 a	8.2 ± 0.2 ab	2.1 ± 0.1 ab	65.4 ± 1.1 ab	108.2 ± 4.8 ab
	N_{160}	54.0 ± 0.8 b	28.4 ± 0.1 b	6.1 ± 0.4 a	8.6 ± 0.2 a	2.2 ± 0.1 ab	66.8 ± 0.1 a	115.0 ± 1.7 a
	N_{240}	52.4 ± 2.7 b	28.1 ± 2.0 b	5.5 ± 0.2 a	8.6 ± 0.1 a	2.3 ± 0.1 a	67.0 ± 1.6 a	119.9 ± 8.7 a
	N_{320}	59.7 ± 2.5 a	32.3 ± 0.6 a	5.1 ± 0.2 a	8.6 ± 0.1 a	2.0 ± 0.1 b	63.7 ± 1.4 b	99.3 ± 0.2 b

In the same year, different lowercase letters within a column indicate significant differences at $p < 0.05$ among the different N treatments.

3.3. Above-Ground Crop N Uptake

Stem and leaf N content decreased as the growth period progressed (Figure 4). At the harvest stage in 2019 and 2020, stem N content increased overall with increasing N rates, and the stem N content in N_{320} increased significantly by 44.9% in 2019 and 40.8% in 2020 compared with N_0 ($p < 0.05$). Moreover, leaf N content values were the lowest in N_0 at the harvest stage in 2019 and 2020 (26.2 and 28.8 mg·g^{-1}) and were significantly lower compared with N_{320} (28.1and 31.6 mg·g^{-1}). At the harvest stage for both years, total N uptake tended to first increase and then decrease with increasing N application rates. Total N uptake values peaked at N_{160} (249.4 kg·ha^{-1} in 2019 and 247.4 kg·ha^{-1} in 2020) and were 25.7% and 36.8% significantly higher compared with N_0, respectively ($p < 0.05$). Stem N uptake values in N_0 were the lowest at the harvest stages (97.4 kg·ha^{-1} in 2019 and 76.5 kg·ha^{-1} in 2020) and were significantly lower compared with N_{160}, N_{240}, and N_{320} for both years.

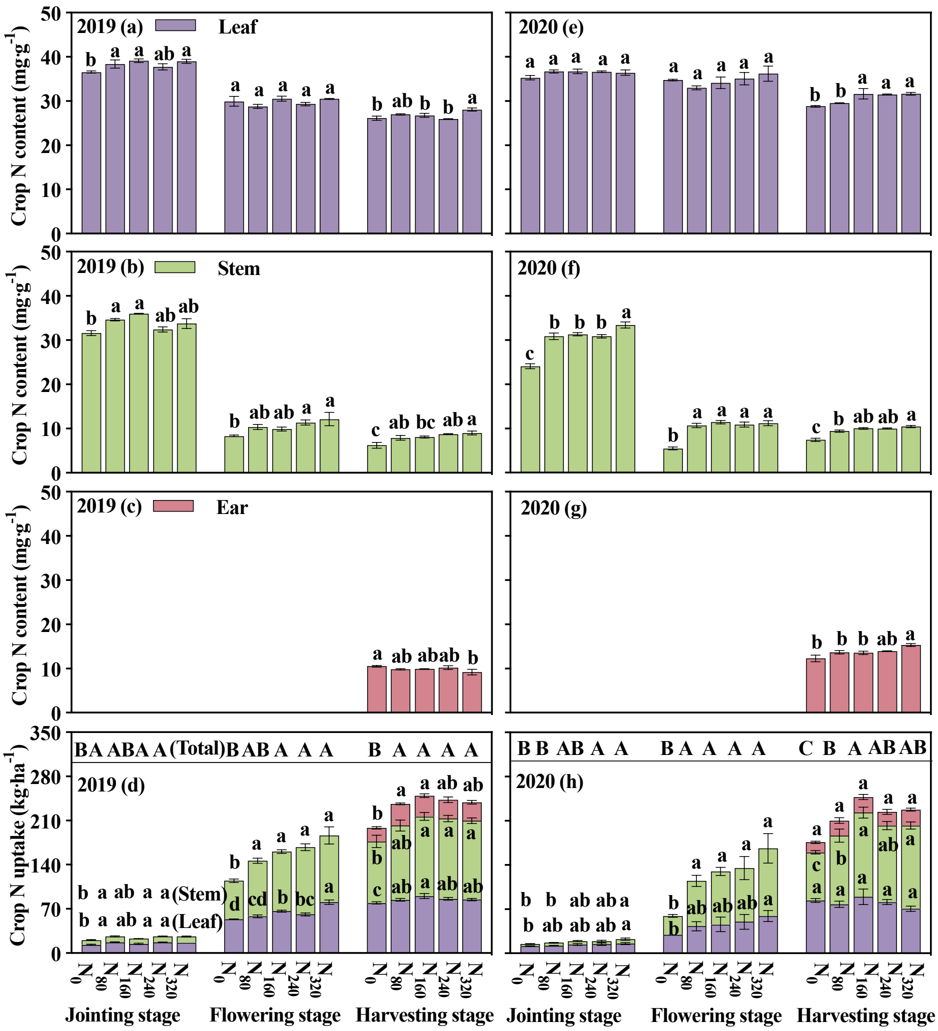

Figure 4. Crop N content to different parts (**a**−**c**,**e**−**g**) and crop N uptake (**d**,**h**) at the jointing, flowering, and harvesting stages of forage sorghum under different N application rates in 2019 and 2020. Different lowercase letters in the same growth stages for the same part (leaf, stem, and ear) represent significant differences at $p < 0.05$ among the different N treatments. Different capital letters in the same growth stages indicate significant differences at $p < 0.05$ in total crop N uptake of forage sorghum among the different N treatments.

3.4. Soil PFP, RE, and NO_3^-–N Residue

In both years, PFP and RE tended to decrease with increasing N rates (Figure 5). PFP and RE responses towards N rates were fitted to linear equations for both years. Maximum PFP (240.2 kg·kg^{-1} in 2019 and 180.6 kg·kg^{-1} in 2020) and RE (45.3% in 2019 and 41.1% in 2020) values were obtained at an N rate of 80 kg·ha^{-1}. Moreover, minimum PFP (38.7 kg·kg^{-1} in 2019 and 34.6 kg·kg^{-1} in 2020) and RE (10.0% in 2019 and 14.2% in 2020) values were obtained at an N rate of 320 kg·ha^{-1}.

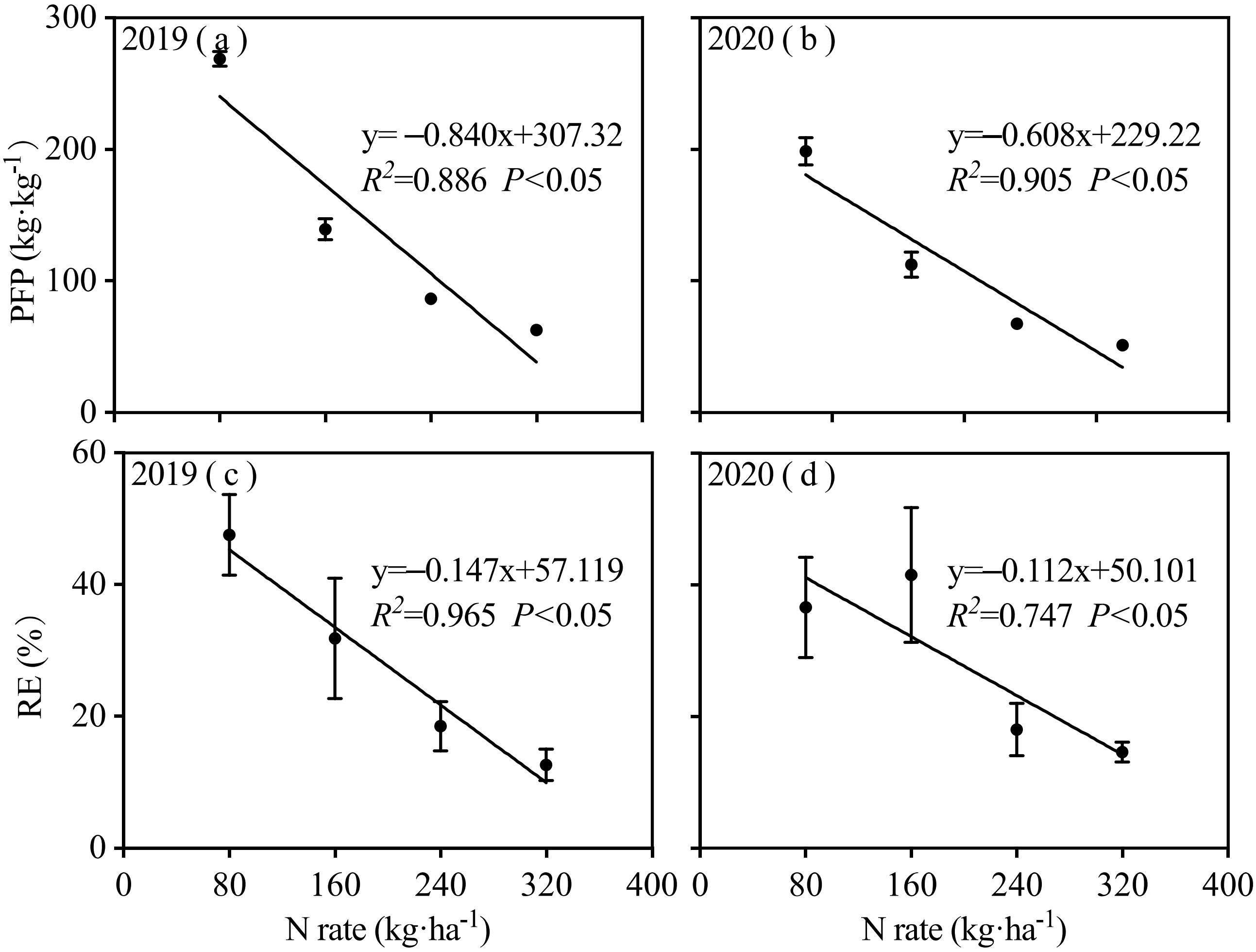

Figure 5. Relationships of PFP (**a**,**b**) and RE (**c**,**d**) of applied N for forage sorghum with different N application rates in 2019 and 2020.

At the jointing stage for both years, NO_3^-–N remained at a high level in the top 0–50 cm soil layer but remained at a low level for the 50–200 cm depths (Figure 6). At the flowering and harvesting stages for both years, NO_3^-–N tended to leach into deeper soil layers (>50 cm). NO_3^-–N residue in the 0–200 cm soil layer was not affected by N rates during the jointing stages in 2019 and 2020 (p > 0.05). NO_3^-–N residue at the flowering stages for both years first increased and then decreased with increasing N rates, and NO_3^-–N residue was the highest in N_{240} (470.0 kg·ha^{-1} in 2019 and 519.9 kg·ha^{-1} in 2020). At the harvest stages for both years, NO_3^-–N residue increased with increasing N rates and peaked at N_{320} (412.2 kg·ha^{-1} in 2019 and 307.9 kg·ha^{-1} in 2020); these values in 2019 and 2020 were 151.3% and 183.2% significantly higher compared with N_0, respectively (p < 0.05).

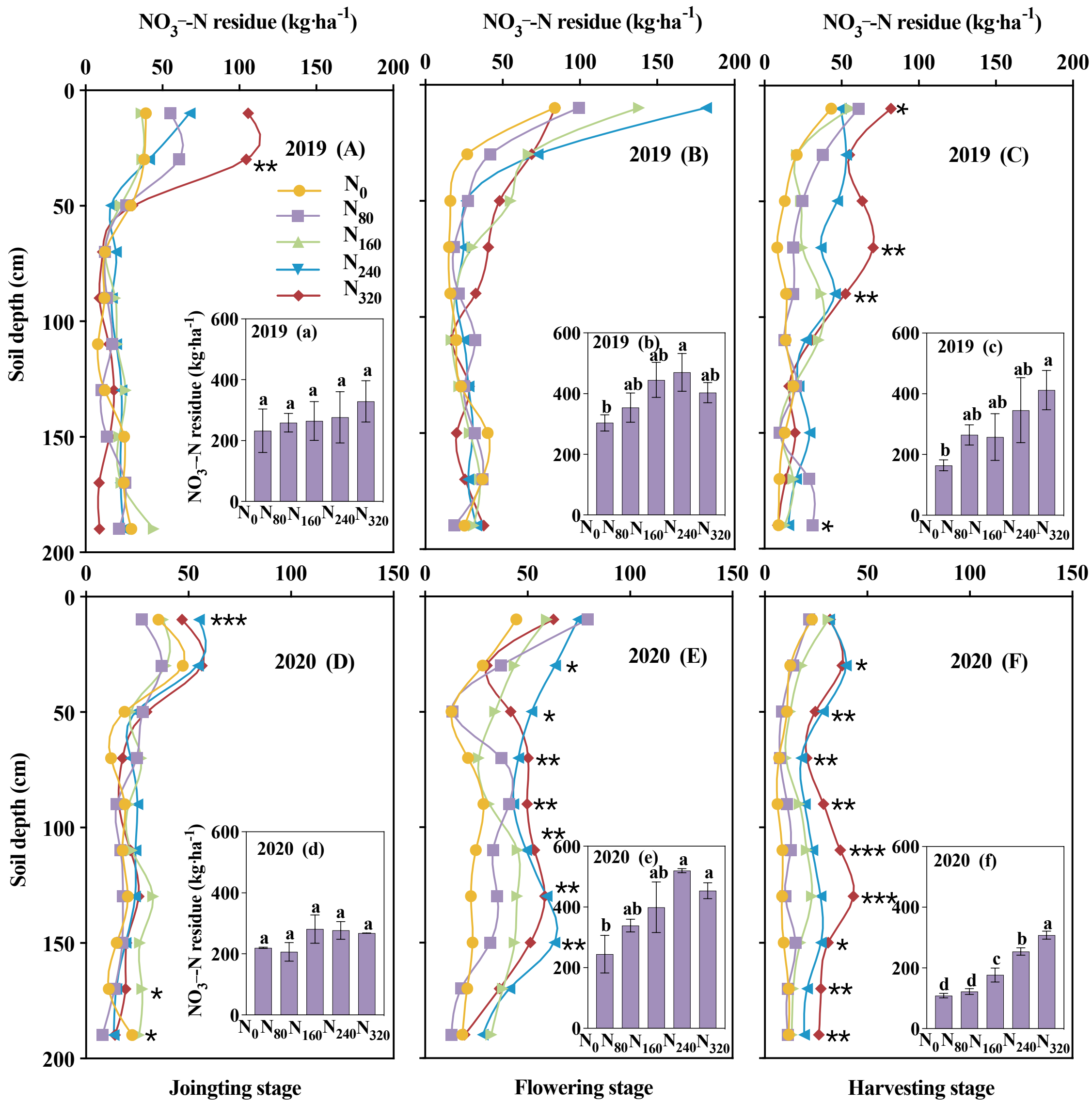

Figure 6. Mean values of NO_3^-−N residue in different soil layer at the jointing (**A**,**D**), flowering (**B**,**E**), and harvesting stages (**C**,**F**) of forage sorghum and the sum of NO_3^-−N residue in the 0−200 cm soil layer under different N application rates in 2019 and 2020 (**A**−**F**). Each point and each bar are the average of six repetitions. Different lowercase letters indicate significant differences at $p < 0.05$ among the different N treatments. *, **, and *** indicate significant differences at $p < 0.05$, $p < 0.01$, $p < 0.001$ at the same soil layer among the different N treatments.

3.5. Nr Losses, GHG Emissions, NF, CF, and EEB

The two-year average Nr losses generally increased with increasing N application rates (Figure 7). The Nr losses increased from 7.2 kg N ha^{-1} in N_0 to 119.0 kg N ha^{-1} in N_{320}, in which about 56.0–70.0% of the Nr losses were derived from NH_3 volatilization, followed by NO_3^- leaching (21.3–31.1%). Only minor Nr losses were caused by direct N_2O emission (4.3–10.0%). Total N_2O emission, as well as N production and transportation, were the main contributors to GHG emissions. Among all the treatments, total N_2O emission induced GHG emissions accounted for 48.8–53.8% of the total GHG emissions, while N fertilizer production and transportation induced GHG emissions accounted for 38.5–43.5%.

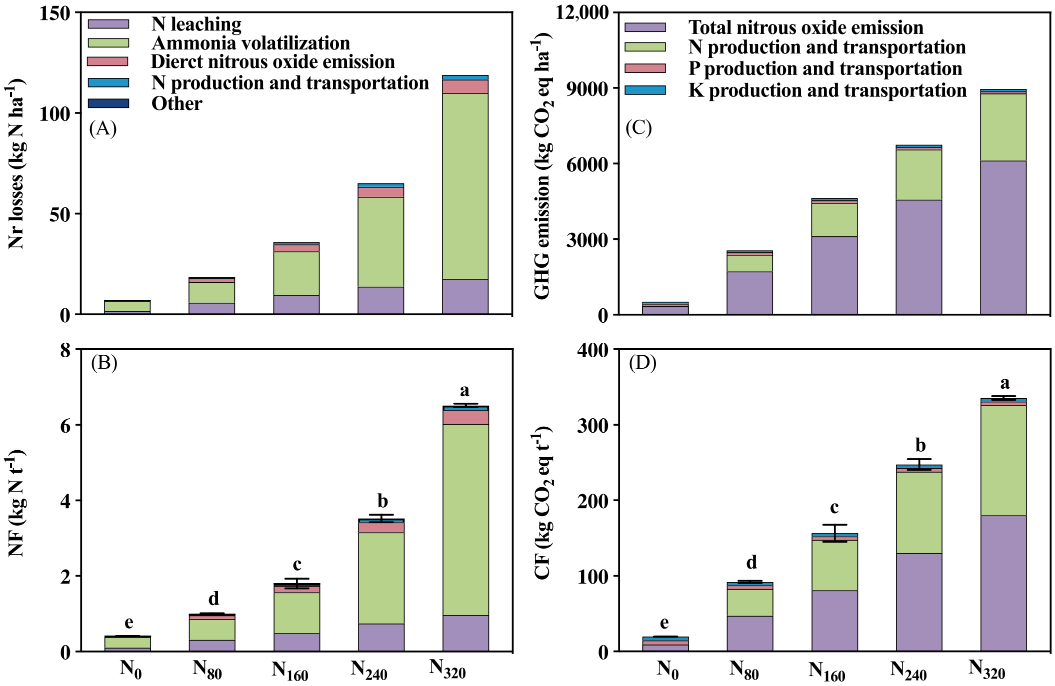

Figure 7. Average Nr losses (**A**), NF (**B**), GHG emissions (**C**), and CF (**D**) across 2019−2020 growing seasons in forage sorghum life cycle as affected by N treatments. Different lowercase letters indicate significant differences at $p < 0.05$ among the different N treatments.

The average NF values for the two years were 0.4, 1.0, 1.8, 3.5, and 6.5 kg N t^{-1} for N_0, N_{80}, N_{160}, N_{240}, and N_{320}, respectively. The NF values for N_{80}, N_{160}, N_{240}, and N_{320} were 144.5%, 340.8%, 761.5%, and 1492.7% higher compared with N_0 ($p < 0.05$). The average two-year CF values for N_0, N_{80}, N_{160}, N_{240}, and N_{320} were 19.6, 92.2, 156.7, 247.6, and 335.5 kg CO_2 eq t^{-1}, respectively. Total N_2O emission, as well as N production and transportation, accounted for 48.8–53.8% and 0–43.5% of CF, followed by P (1.5–27.4%) and K (1.3–23.8%) production and transportation.

During the forage sorghum life cycle, as N rates increased, the N-derived benefits initially peaked at N_{160} (up to 624.4 USD·ha^{-1}) and then decreased; however, the ecological and human health costs continuously increased (Table 3). Private profitability increased with increasing N application rates to 514.2 USD·ha^{-1} (N_{160}), and then decreased to 56.2 USD·ha^{-1} (N_{240}) and −55.8 USD·ha^{-1} (N_{320}). Finally, EEB was similar in trend to private profitability.

Table 3. Mean costs and benefits of forage sorghum production under different N treatments across 2019–2020.

Treatments	N-Derived Benefits (USD·ha^{-1})	N Costs (USD·ha^{-1})	Labor Costs (USD·ha^{-1})	Ecological Costs (USD·ha^{-1})	Health Costs (USD·ha^{-1})	Private Profitability (USD·ha^{-1})	Ecosystem Economic Benefits (USD·ha^{-1})
N_0	0.0	0.0	3.9	14.1	6.3	−3.9	−24.3
N_{80}	266.7	51.2	7.8	50.3	15.4	207.7	142.1
N_{160}	624.4	102.4	7.8	90.7	30.8	514.2	392.7
N_{240}	217.6	153.6	7.8	139.8	59.4	56.2	−143.0
N_{320}	156.8	204.8	7.8	207.0	115.2	−55.8	−377.9

4. Discussion

4.1. Plant Growth, Dry Matter Yield, and Nutrient Quality

Appropriate N fertilizer application significantly increased forage sorghum height and stem diameter [3,47]. Specifically, plant height and stem diameter were significantly higher (7.7% and 9.3%) at N_{160} compared with N_0 at the harvest stage in 2020, which agreed well with the results of Afzal et al. [48], who reported that forage sorghum height and stem diameter were 25.2% and 71.4% higher at an N application rate of 57.5 kg $N \cdot ha^{-1}$ compared with the zero N treatment. Several studies have reported that N fertilizer influences LAI [49]. Our study showed that forage sorghum LAI first increased and then decreased with increasing N application rates at the harvest stage during both years. Moreover, the largest LAI values appeared in N_{160} at the harvest stage, which were 5.1% and 12.3% significantly higher compared with N_0, respectively. This may be due to insufficient plant nutrient supply in N_0 (no N applied), which results in fewer and smaller plant leaves. Additionally, excessive N application results in denser leaves, thereby creating inadequate lighting for the lower and middle plant parts, thus leading to premature leaf wilting and decreased LAI.

Sorghum yield can greatly be increased by utilizing moderate N application rates [50,51], but excessive or insufficient N application rates can reduce yield [14]. When N application levels are too high, excessive leaf growth and poor population ventilation is promoted, and the lower and middle leaves do not receive enough light, which negatively affects photosynthetic product formation and leads to yield reduction. In this study, the forage sorghum N requirement was sufficient at a 160 $kg \cdot ha^{-1}$ N application rate. In contrast, when the N application rate exceeded 160 $kg \cdot ha^{-1}$, the above-ground dry matter yield at the harvest stages decreased. Lower NDF and ADF levels improve food digestibility in ruminants, and thus increases nutrient intake. Therefore, lower NDF and ADF levels exhibit better forage quality. A high N application rate (N_{320}) significantly increased NDF and ADF at the harvest stages. Tang et al. [51] similarly concluded that sorghum NDF and ADF increased by 4.5% and 1.4%, respectively, at a 240 $kg \cdot ha^{-1}$ N application rate compared with no N application. ASH content at the harvest stage was not affected by N input. Qu et al. [52] and Zhang et al. [53] generated similar results and demonstrated limited effects of N application on sorghum ASH, but a more significant impact from genes. Furthermore, Monti et al. [54] reported that ASH was influenced more by P and K fertilizer. For CP content, the results of this study are similar to previous studies, which concluded that sorghum CP content at the harvest stage significantly increased with increased N application rates [14,51]. Highly desirable quality elements, such as DMI, DDM, and RFV, benefit forage quality and thereby enhance the capacity of livestock to utilize forage nutrients [21,55]. In our study, high N application rates (N_{320}) significantly reduced forage sorghum RFV, whereas low and medium N application rates (N_0, N_{80}, N_{160}, and N_{240}) did not produce significant differences.

4.2. Crop N Uptake, NUE, and NO_3^-–N Residue

An appropriate N application rate can improve crop production capacity and promote plant N uptake. During both growing seasons in this study, forage sorghum N uptake at the harvest stages was significantly higher in N treatments compared with N_0. This result is consistent with other studies [56,57]. N fertilization may increase crop N uptake by stimulating root growth. Furthermore, the crop N uptake in different N rates at the harvest stage was higher than the amount of N fertilizer we applied. On the one hand, a considerable part of the N absorbed by crops comes from the mineralized N, and the application of N fertilizer increases the soil N source, which can improve soil physicochemical properties and increase the number and activity of soil microorganisms, thus promoting the mineralization of soil organic N [58]. On the other hand, global N deposition has continued to increase in the last hundred years, and the rate of increase is rising [59]. He et al. found that total airborne N inputs to a maize-wheat rotation system on the North China ranged from 99 to 117 kg N ha^{-1} yr^{-1} [60]. Therefore, crop N uptake can be higher than the applied N fertilizer. N application increased stem N uptake at the harvest stages, which was similar to previous studies. For example, Cosentino et al. [61] showed that the forage sorghum stem N uptake increased by 69.6%, 58.5%, and 67.0% at 60, 120, and 180 kg·ha^{-1} N application rates, respectively, compared with the zero N treatment. Abunyewa et al. [62] also found similar results.

PFP and RE are common indicators that express crop NUE in different ways. In this study, PFP and RE decreased significantly with increasing N application. Ju [63] and Abunyewa et al. [62] showed that excessive N application resulted in reduced plant yield increase. This is possibly due to the fact that a high N fertilizer application depresses plant root growth, and the subsequent reduction in root length and absorption area affects root system nutrient uptake rates [64,65].

Soil mineral N content gradually increases with increasing N fertilizer application [66], and NO_3^-–N is the main N form present in the soil, which is used by crops. In both growing seasons, NO_3^-–N residue in the 0–200 m soil layer increased significantly with increasing N application. Scordia et al. [38] similarly concluded that N application rates of 120 and 240 kg·ha^{-1} significantly increased soil NO_3^-–N residue. Wang et al. [67] also showed that soil NO_3^-–N residue was highly correlated with N application rate. In this study, NO_3^-–N residue in N_{320} at the harvest stage in 2020 increased by 74.1% compared with N_{160}. This indicates that a two-year successive application of excessive N fertilizer leads to significant NO_3^-–N residue in deeper soil layers. Ju et al. [68] showed that 20.9–48.4% of N fertilizer remains in the soil after the crop is harvested. Since farmers tend to apply large amounts of N fertilizer every year, a large amount of NO_3^-–N remains in the soil profile after crop harvest, and if heavy rains are encountered, NO_3^-–N can move deeper. This NO_3^-–N is unavailable for crop use, ultimately entering the groundwater and atmosphere through leaching, nitrification, and denitrification, thereby causing potential environmental risks [67,69]. The use of cover crops and controlled-release urea can be promising measures to increase crop NUE and reduce the N losses to the environment [70]. In our study, NO_3^-–N residue in 2020 was lower than in 2019, this may be caused by higher rainfall in 2019 than in 2020. High intensity precipitation can cause NO_3^-–N residue in the soil to leach deeper into the soil, resulting in ineffective NO_3^-–N residue below the root zone, which cannot be detected [71]. In addition, NO_3^-–N residue in the 0–200 cm soil layer at harvest stage was higher than the amount of N fertilizer applied in 2019 and 2020. This is understandable since the in-season N fertilizer is not the sole source of NO_3^-–N residue in soil, the NO_3^-–N residue before sowing, mineralization of soil organic N, and increasing global N deposition in agroecosystems also made a big contribution

4.3. Nr losses, Private Profitability, and EEB

Increased N fertilizer application has played an irreplaceable role in improving crop yields, as well as the economic benefits for farmers. However, the overuse of N fertilizer has resulted in increased Nr losses, which has negatively impacted the global N cycle and has caused numerous environmental problems. To achieve sustainable land use, farmland Nr losses must be understood. NO_3^- leaching, N_2O emission, and NH_3 volatilization are the main Nr loss pathways from farmland [72]. In this study, NO_3^- leaching, N_2O emission, and NH_3 volatilization increased with increasing N application. Zhang et al. [25] and Yao et al. [73] reached similar conclusions: Nr losses increased with increasing N application. Therefore, a suitable N fertilizer application rate must be selected to prevent major environmental problems.

EEB and private profitability reached a maximum value at N_{160}. Therefore, when accounting for dry matter yield, a 160 kg·ha^{-1} N application rate can maximize forage sorghum above-ground dry matter yield while maintaining a high private profitability and EEB. This study also demonstrated that using common urea (CU) results in higher ecological and health costs. Zhang et al. [25] showed that the ecological and health costs of controlled-release urea and urea blends (BU) were 14.7% and 20.1%, respectively, lower than

CU. Moreover, BU can be applied at once, which reduces the labor cost by half. Therefore, widespread BU use can be considered in future agricultural production.

Both in-season N fertilizer application and soil basic fertility condition before sowing have notable influences on yield performance and Nr losses, thus influencing private profitability and EEB. This two-year N application study was performed on a typical cropland with history of farmer conventional fertilization and management. The basic fertility of the cropland used in this study has good representatives of soil fertility condition in the area. So the yield response to fertilizer N application and Nr losses, private profitability, and EEB can possibly vary significantly when the same study is performed on sites with different soil basic fertilities. This two-year successive study was conducted on the same typical cropland to investigate the cumulative effect of two seasons of N application on yield performance, quality, and N-use efficiency in forage sorghum production. This is essentially important in optimizing N application for forage sorghum to maximize yield, quality, and N use efficiency while reducing environmental costs.

5. Conclusions

This study indicated that forage sorghum above-ground dry matter yield and N uptake initially increased and then decreased with increasing N application (both reached a maximum value at the 160 $kg \cdot ha^{-1}$ N rate, with a two-year average of 20.1 $t \cdot ha^{-1}$ and 248.4 $kg \cdot ha^{-1}$, respectively). Similarly, forage sorghum CP content at the 160 $kg \cdot ha^{-1}$ N rate was significantly higher compared with the zero-N treatment, but NDF, ADF, and RFV were not significantly different. Nr losses, GHG emission, NF, and CF continuously increased with increasing N application. Private profitability and EEB were maximized at the 160 $kg \cdot ha^{-1}$ N rate. Simply increasing the N fertilizer amount will not increase yield, but will indeed raise the economic costs for farmers and negatively impact the environment. Therefore, we propose that 160 $kg \cdot ha^{-1}$ is the ideal N application rate for forage sorghum in the dry region of the Loess Plateau. This will ensure optimum yield and forage quality, as well as improve farmer income and reduce environmental pollution.

Author Contributions: Conceptualization, X.Y., N.S., C.J. and R.M.; methodology, W.G.; software, W.G.; validation, W.G.; formal analysis, W.G.; investigation, W.G. and N.S.; resources, W.G. and N.S.; data curation, W.G.; writing—original draft preparation, W.G.; writing—review and editing, W.G.; visualization, W.G.; supervision, X.Y.; project administration, X.Y.; funding acquisition, X.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Plan (2021YFD1100501), the Natural Science Foundation of Gansu Province (21JR7RA488), the National Forage Industry Technology System (CARS-34), and the Fundamental Research Funds for the Central Universities of Lanzhou University (lzujbky-2021-14).

Data Availability Statement: Not applicable.

Acknowledgments: We would like to thank the State Key Laboratory of Grassland Agro-ecosystems, Lanzhou University for the use of its facility. And we are also very appreciative of Juncheng Li's help in field sampling.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Nr losses and GHG emission for production and transportation of various agricultural inputs in the forage sorghum production system.

Item	Unit	Nr Losses (10^{-3} kg N·Unit^{-1})	GHG Gases Emission (kg CO_2 eq·Unit^{-1})	Reference
N production and transportation	kg N	7.15	8.30	Zhang et al. (2013) Cui et al. (2013) Yue et al. (2013)
P production and transportation	Kg P_2O_5	0.184	0.79	
K production and transportation	Kg K_2O	0.146	0.55	

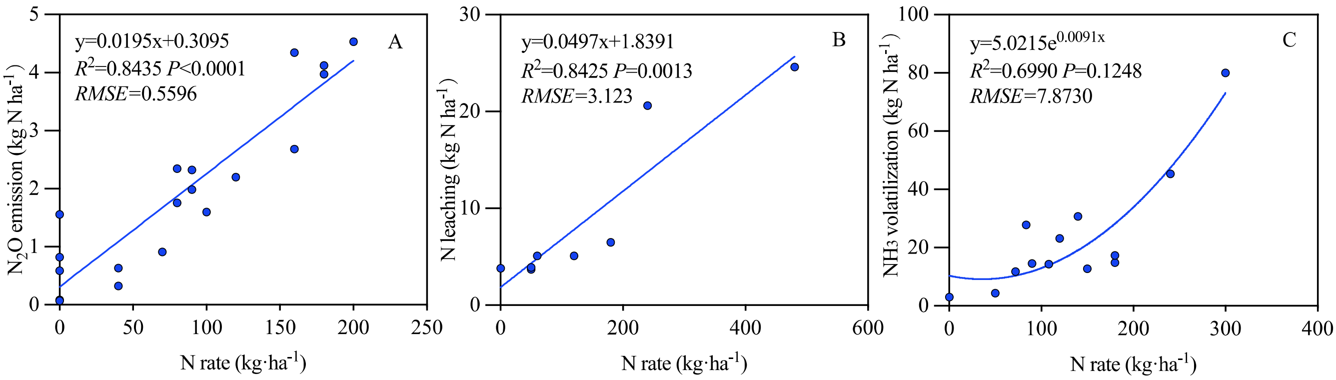

Figure A1. Relationships between N application rate and total N_2O emission (**A**), N leaching (**B**), NH_3 volatilization (**C**) with common urea for forage sorghum production.

References

1. Da Silva, P.C.G.; Tiritan, C.S.; Echer, F.R.; Cordeiro, C.F.D.S.; Rebonatti, M.D.; Carlos, H.D.S. No-tillage and crop rotation increase crop yields and nitrogen stocks in sandy soils under agroclimatic risk. *Field Crops Res.* **2020**, *258*, 107947. [CrossRef]
2. Vasilakoglou, I.; Dhima, K.; Karagiannidis, N.; Gatsis, T. Sweet sorghum pro-ductivity for biofuels under increased soil salinity and reduced irrigation. *Field Crops Res.* **2011**, *120*, 38–46. [CrossRef]
3. Sawargaonkar, G.L.; Patil, M.D.; Wani, S.P.; Pavani, E.; Reddy, B.V.S.R.; Marimuthu, S. Nitrogen response and water use efficiency of sweet sorghum cultivars. *Field Crops Res.* **2013**, *149*, 245–251. [CrossRef]
4. Farré, I.; Faci, J.M. Comparative response of maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench) to deficit irrigation in a Mediterranean environment. *Agric. Water Manag.* **2006**, *83*, 135–143. [CrossRef]
5. Oliver, A.L.; Grant, R.J.; Pedersen, J.F.; O'Rear, J. Comparison of brown midrib-6 and -18 forage sorghum with conventional sorghum and corn silage in diets of lactating dairy cows. *J. Dairy Sci.* **2004**, *87*, 637–644. [CrossRef]
6. Miron, J.; Zuckerman, E.; Adin, G.; Solomon, R.; Ezra, S.; Nikbachat, M.; Yosef, E.; Zenou, A.; Weinberg, Z.G.; Chen, Y.; et al. Comparison of two forage sorghum varieties with corn and the effect of feeding their silages on eating behavior and lactation performance of dairy cows. *Anim. Feed Sci. Tech.* **2007**, *139*, 23–39. [CrossRef]
7. Hao, B.; Xue, Q.; Bean, B.W.; Rooney, W.L.; Becker, J.D. Biomass production, water and nitrogen use efficiency in photoperiod-sensitive sorghum in the Texas High Plains. *Biomass Bioenergy* **2014**, *62*, 108–116. [CrossRef]
8. Marsalis, M.A.; Angadi, S.V.; Contreras-Govea, F.E. Dry matter yield and nutritive value of corn, forage sorghum, and BMR forage sorghum at different plant populations and nitrogen rates. *Field Crops Res.* **2010**, *116*, 52–57. [CrossRef]
9. Barbanti, L.; Grandi, S.; Vecchi, A.; Venturi, G. Sweet and fibre sorghum (*Sorghum bicolor* (L.) Moench), energy crops in the frame of environmental protection from excessive nitrogen loads. *Eur. J. Agron.* **2006**, *25*, 30–39. [CrossRef]
10. Cui, Z.L.; Zhang, F.S.; Miao, Y.X.; Sun, Q.P.; Fei, L.; Chen, X.P.; Li, J.L.; Ye, Y.L.; Yang, Z.P.; Zhang, Q.; et al. Soil nitrate-N levels required for high yield maize production in the North China Plain. *Nutr. Cycl. Agroecosyst.* **2008**, *82*, 187–196. [CrossRef]
11. Nematpour, A.; Eshghizadeh, H.R.; Zahedi, M. Comparing the Corn, Millet and Sorghum as Silage Crops under Different Irrigation Regime and Nitrogen Fertilizer Levels. *Int. J. Plant Prod.* **2021**, *15*, 351–361. [CrossRef]
12. Delevatti, L.M.; Cardoso, A.S.; Barbero, R.P.; Leite, R.G.; Romanzini, E.P.; Ruggieri, A.C.; Reis, R.A. Effect of nitrogen application rate on yield, forage quality, and animal performance in a tropical pasture. *Sci. Rep.* **2019**, *9*, 7596. [CrossRef] [PubMed]

13. Sher, A.; Hassan, F.U.; Ali, H.; Hussain, M.; Sattar, A. Enhancing forage quality through appropriate nitrogen dose, seed rate and harvest stage, in sorghum cultivars grown in Pakistan. *Grassl. Sci.* **2017**, *63*, 15–22. [CrossRef]
14. Restelatto, R.; Pavinato, P.S.; Sartor, L.R.; Paixao, S.J. Production and nutritional value of sorghum and black oat forages under nitrogen fertilization. *Grass Forage Sci.* **2014**, *69*, 693–704. [CrossRef]
15. Ju, X.T.; Gu, B.J. Status-quo, problem and trend of nitrogen fertilization in China. *J. Plant Nutr. Fertil.* **2014**, *20*, 783–795. (In Chinese) [CrossRef]
16. Sharma, P.; Shukla, M.K.; Sammis, T.W.; Steiner, R.L.; Mexal, J.G. Nitrate-nitrogen leaching from three specialty crops of New Mexico under furrow irrigation system. *Agric. Water Manag.* **2012**, *109*, 71–80. [CrossRef]
17. Behera, S.N.; Sharma, M.; Aneja, V.P.; Balasubramanian, R. Ammonia in the atmosphere: A review on emission sources, atmospheric chemistry and deposition on terrestrial bodies. *Environ. Sci. Pollut. R.* **2013**, *20*, 8092–8131. [CrossRef]
18. Sun, H.F.; Zhou, S.; Zhang, J.; Zhang, X.X.; Wang, C. Effects of controlled-release fertilizer on rice grain yield, nitrogen use efficiency and greenhouse gas emissions in a paddy field with straw incorporation. *Field Crop. Res.* **2020**, *253*, 107814. [CrossRef]
19. Abdo, A.I.; Shi, D.; Li, J.; Yang, T.; Wang, X.F.; Li, H.T.; Abdel-Hames, E.M.W.; Merwad, A.M.A.; Wang, L.Q. Ammonia emission from staple crops in China as response to mitigation strategies and agronomic conditions: Meta-analytic study. *J. Clean. Prod.* **2021**, *279*, 123835. [CrossRef]
20. Yang, S. *Feedstuff Analysis and Identification and Determination of Feedstuff Quality*; Beijing Agricultural University Press: Beijing, China, 1993. (In Chinese)
21. Lithourgidis, A.S.; Vasilakoglou, I.B.; Dhima, K.V.; Dordas, C.A.; Yiakoulaki, M.D. Forage yield and quality of common vetch mixtures with oat and triticale in two seeding ratios. *Field Crops Res.* **2006**, *99*, 106–113. [CrossRef]
22. Jahanzad, E.; Jorat, M.; Moghadam, H.; Sadeghpour, A.; Chaichi, M.R.; Dashtaki, M. Response of a new and a commonly grown forage sorghum cultivar to limited irrigation and planting density. *Agric. Water Manag.* **2013**, *117*, 62–69. [CrossRef]
23. Yang, X.L.; Lu, Y.L.; Ding, Y.; Yin, X.F.; Raza, S.; Tong, Y. Optimising nitrogen fertilisation: A key to improving nitrogen-use efficiency and minimising nitrate leaching losses in an intensive wheat/maize rotation (2008–2014). *Field Crops Res.* **2017**, *206*, 1–10. [CrossRef]
24. Yang, X.L.; Lu, Y.L.; Tong, Y.A.; Yin, X.F. A 5-year lysimeter monitoring of nitrate leaching from wheat–maize rotation system: Comparison between optimum N fertilization and conventional farmer N fertilization. *Agric. Ecosyst. Environ.* **2015**, *199*, 34–42. [CrossRef]
25. Zhang, L.; Liang, Z.Y.; Hu, Y.C.; Schmidhalter, U.; Zhang, W.S.; Ruan, S.Y.; Chen, X.P. Integrated assessment of agronomic, environmental and ecosystem economic benefits of blending use of controlled-release and common urea in wheat production. *J. Clean. Prod.* **2021**, *287*, 125572. [CrossRef]
26. Zhang, W.F.; Dou, Z.X.; He, P.; Ju, X.T.; Powlson, D.; Chadwick, D.; Norse, D.; Lu, Y.L.; Zhang, Y.; Wu, L.; et al. New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 8375–8380. [CrossRef] [PubMed]
27. Cui, Z.L.; Yue, S.C.; Wang, G.L.; Zhang, F.S.; Chen, X.P. In-season root-zone N management for mitigating greenhouse gas emission and reactive N losses in intensive wheat production. *Environ. Sci. Technol.* **2013**, *47*, 6015–6022. [CrossRef]
28. Yue, S.C. Optimum Nitrogen Management for High-Yielding Wheat and Maize Cropping System. Ph.D. Thesis, China Agricultural University, Beijing, China, 2013. (In Chinese).
29. Zougmore, R.; Mando, A.; Stroosnijder, L.; Guillobez, S. Nitrogen flows and balances as affected by water and nutrient management in a sorghum cropping system of semiarid Burkina Faso. *Field Crops Res.* **2004**, *90*, 235–244. [CrossRef]
30. Li, Z.X.; Dong, S.T.; Wang, K.J.; Zhang, J.W.; Liu, P.; Wang, Q.C.; Liu, C.X. In situ study influence of different fertilization strategies for summer maize on soil nitrogen leaching and volatilization. *Plant Nutr. Fertil. Sci.* **2007**, *13*, 998–1005. (In Chinese) [CrossRef]
31. Su, F.; Ding, X.Q.; Gao, Z.L.; Huang, B.X.; Chen, X.P.; Zhang, F.S.; Kogge, M.; Romheld, V. Ammonia volatilization from nitrogen fertilizer of winter wheat-summer maize system in the North Chia Plain. *China Environ. Sci.* **2007**, *27*, 409–413. (In Chinese) [CrossRef]
32. Massimiliano, D.; Bell, M.J.; Grace, P.R.; Roelings, D.W.; Scheer, C.; Strazzabosco, A. Assessing agronomic and environmental implications of different N fertilisation strategies in subtropicalgrain cropping systems on Oxisols. *Nutr. Cycl. Agroecosyst.* **2014**, *100*, 369–382. [CrossRef]
33. Li, Q.Q.; Li, Y.F.; Gao, Q.; Li, S.Q.; Chen, X.P.; Zhang, F.S.; Liu, X.J. Effect of conventional and optimized nitrogen fertilization on spring maize yield, ammonia volatiolization and nitrogen balance in soil- maize system. *J. Plant Nutr. Fertil.* **2015**, *21*, 571–579. (In Chinese) [CrossRef]
34. Schwenke, G.D.; Haigh, B.M. The interaction of seasonal rainfall and nitrogen fertiliser rate on soil N_2O emission, total N loss and crop yield of dryland sorghum and sunflower grown on sub-tropical Vertosols. *Soil Res.* **2016**, *54*, 604. [CrossRef]
35. Zhou, L.P.; Ynag, L.P.; Bai, L.Y.; Lu, Y.L.; Wang, L.; Ni, L. Comparison of several slow-released nitrogen fertilizers in ammonia vplatiolization and nitrogen utilization in summer maize field. *J. Plant Nutr. Fertil.* **2016**, *22*, 1449–1457. (In Chinese) [CrossRef]
36. Fontes, G.P.; Tomlinson, P.J.; Roozeboom, K.L.; Warren, J.; Diaz, D.A.R. Nitrogen fertilization offsets the N_2O mitigating effects of cover-crops and double-crop soybean in a wheat–sorghum system. *Agron. J.* **2020**, *112*, 772–785. [CrossRef]
37. Shan, N.; Zhao, T.K.; Tu, F.L.; An, Z.Z.; He, Y.K.; Hao, Y.C.; Sun, X.J.; Chuan, L.M. Ammonia volatilization from maize cropland under different N application at a rural area of central Northern China Plain. *Soil Fertil. Sci. China* **2020**, *4*, 32–40. (In Chinese) [CrossRef]

38. Scordia, D.; Cosentino, S.L.; Mantineo, M.; Testa, G.; Patane, C. Nitrogen balance in a sweet sorghum crop in a Mediterranean environment. *Agronomy* **2021**, *11*, 1292. [CrossRef]
39. Intergovernmental Panel on Climate Change. Climate Change 2013: The Physical Science Basis. In *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2013.
40. Perrin, A.; Basset-Mens, C.; Gabrielle, B. Life cycle assessment of vegetable products: A review focusing on cropping systems diversity and the estimation of field emissions. *Int. J. Life Cycle Assess.* **2014**, *19*, 1247–1263. [CrossRef]
41. Ying, H.; Ye, Y.L.; Cui, Z.L.; Chen, X.P. Managing nitrogen for sustainable wheat production. *J. Clean. Prod.* **2017**, *162*, 1308–1316. [CrossRef]
42. Xia, Y.Q.; Yan, X.Y. Ecologically optimal nitrogen application rates for rice cropping in the Taihu Lake region of China. *Sustain. Sci.* **2012**, *7*, 33–44. [CrossRef]
43. Li, B.; Fan, C.H.; Zhang, H.; Chen, Z.Z.; Sun, L.Y.; Xiong, Z.Q. Combined effects of nitrogen fertilization and biochar on the net global warming potential, greenhouse gas intensity and net ecosystem economic budget in intensive vegetable agriculture in southeastern China. *Atmos. Environ.* **2015**, *100*, 10–19. [CrossRef]
44. Xiang, P.A.; Zhou, Y.; Jiang, J.A.; Zheng, H.; Yan, H.M.; Huang, H. Studies on the external costs of and the optimum use of nitrogen fertilizer based on the balance of economic and ecological benefits in the paddy field system of the Dongting Lake area. *Agric. Sci. China* **2006**, *39*, 2531–2537. [CrossRef]
45. Xia, Y.Q.; Yan, X.Y. Comparison of statistical models for predicting cost effective nitrogen rate at rice-wheat cropping systems. *Soil Sci. Plant Nutr.* **2011**, *57*, 320–330. [CrossRef]
46. Gu, B.J.; Ge, Y.; Ren, Y.; Xu, B.; Luo, W.D.; Jiang, H.; Gu, B.H.; Chang, J. Atmospheric reactive nitrogen in China: Sources, recent trends, and damage costs. *Environ. Sci. Technol.* **2012**, *46*, 9420–9427. [CrossRef]
47. Shehab, A.A.; Guo, Y.J. Effects of nitrogen fertilization and drought on hydrocyanic acid accumulation and morpho-physiological parameters of sorghums. *J. Sci. Food Agric.* **2021**, *101*, 3355–3365. [CrossRef] [PubMed]
48. Afzal, M.; Ahmad, A.U.H.; Zamir, S.I.; Khalid, F.; Mohsin, A.U.; Gillani, S.M.W. Performance of multicut forage sorghum under various sowing methods and nitrogen application rates. *J. Anim. Plant Sci.* **2013**, *23*, 232–239. [CrossRef]
49. Yang, G.D.; Hu, Z.Y.; Zhou, Y.F.; Hao, Z.Y.; Li, J.H.; Wang, Q.; Meng, X.M.; Huang, R.D. Effects of nitrogen application strategy and planting density optimization on sorghum yield and quality. *Agron. J.* **2021**, *113*, 1–13. [CrossRef]
50. Anfinrud, R.; Cihacek, L.; Johnson, B.L.; Ji, Y.; Berti, M.T. Sorghum and kenaf biomass yield and quality response to nitrogen fertilization in the Northern Great Plains of the USA. *Ind. Crop Prod.* **2013**, *50*, 159–165. [CrossRef]
51. Tang, C.C.; Yang, X.L.; Chen, X.; Ameen, A.; Xie, G.H. Sorghum biomass and quality and soil nitrogen balance response to nitrogen rate on semiarid marginal land. *Field Crops Res.* **2018**, *215*, 12–22. [CrossRef]
52. Qu, H.; Liu, X.B.; Dong, C.F.; Lu, X.Y.; Shen, Y.X. Field performance and nutritive value of sweet sorghum in eastern China. *Field Crops Res.* **2014**, *157*, 84–88. [CrossRef]
53. Zhang, S.J.; Chaudhry, A.S.; Ramdani, D.; Osman, A.; Guo, X.F.; Edwards, G.R.; Cheng, L. Chemical composition and in vitro fermentation characteristics of high sugar forage sorghum as an alternative to forage maize for silage making in Tarim Basin, China. *J. Integr. Agric.* **2016**, *15*, 175–182. [CrossRef]
54. Monti, A.; Virgilio, D.N.; Venturi, G. Mineral composition and ash content of six major energy crops. *Biomass Bioenergy* **2008**, *32*, 216–223. [CrossRef]
55. Carmi, A.; Aharoni, Y.; Edelstein, M.; Umiel, N.; Hagiladi, A.; Yosef, E.; Nikbachat, M.; Zenou, A.; Miron, J. Effects of irrigation and plant density on yield, composition and in vitro digestibility of a new forage sorghum variety, Tal, at two maturity stages. *Anim. Feed. Sci. Technol.* **2006**, *131*, 121–133. [CrossRef]
56. Velinov, I.; Todorov, Z.; Kostadinova, S. Accumulation and Distribution of Dry Mass and Nitrogen in Sorghum Plants Grown at Different Nutritional Level. *Agronomy Series of Scientific Research/Lucrari Stiintifice Seria Agronomie* **2019**, *62*. Available online: https://agronomyjournal.usamv.ro/pdf/2019/issue_1/Art30.pdf (accessed on 19 June 2022).
57. Bayu, W.; Rethman, N.F.G.; Hammes, P.S. Effects of tied-ridge, nitrogen fertilizer and cultivar on the yield and nitrogen use efficiency of sorghum in semi-arid Ethiopia. *Arch. Agron. Soil Sci.* **2012**, *58*, 547–560. [CrossRef]
58. He, Y.T.; Zhang, W.J.; Xu, M.G.; Tong, X.G.; Sun, F.X.; Wang, J.Z.; Huang, S.M.; Zhu, P.; He, X.H. Long-term combined chemical and manure fertilizations increase soil organic carbon and total nitrogen in aggregate fractions at three typical cropland soils in China. *Sci. Total Environ.* **2015**, *532*, 635–644. [CrossRef] [PubMed]
59. Kanakidou, M.; Myriokefalitakis, S.; Daskalakis, N.; Fanourgakis, G.; Nenes, A.; Baker, A.R.; Tsigaridis, K.; Mihalopoulos, N. Past, present, and future atmospheric nitrogen deposition. *J. Atmos. Sci.* **2016**, *73*, 2039–2047. [CrossRef] [PubMed]
60. He, C.E.; Wang, X.; Liu, X.J.; Fangmeier, A.; Christie, P.; Zhang, F.S. Nitrogen deposition and its contribution to nutrient inputs to intensively managed agricultural ecosystems. *Ecol. Appl.* **2010**, *20*, 80–90. [CrossRef]
61. Cosentino, S.L.; Mantineo, M.; Testa, G. Water and nitrogen balance of sweet sorghum [*Sorghum bicolor* moench(L.)] cv. Keller under semi-arid conditions. *Ind. Crop Prod.* **2012**, *36*, 329–342. [CrossRef]
62. Abunyewa, A.A.; Ferguson, R.B.; Wortmann, C.S.; Mason, S.C. Grain sorghum nitrogen use as affected by planting practice and nitrogen rate. *J. Soil Sci. Plant Nutr.* **2017**, *17*, 155–166. [CrossRef]
63. Ju, X.T. The concept and meanings of nitrogen fertilizer availability ratio discussing misunderstanding of traditional nitrogen use efficiency. *Acta Pedol. Sin.* **2014**, *51*, 921–933. (In Chinese) [CrossRef]

64. Graves, P. Measuring Root Growth Response to Nitrogen Fertilization Rates in Young Pecan Seedlings Using the Minirhizotron Method. Master's Thesis, Texas A & M University, College Station, TX, USA, 2014. Available online: https://hdl.handle.net/1969.1/154136 (accessed on 19 June 2022).
65. Jiang, W.H.; Wang, K.J.; Wu, Q.P.; Dong, S.T.; Liu, P.; Zhang, J.W. Efects of narow plant spacing on root distribution and physiological nitrogen use eficiency in summer maize. *Crop J.* **2013**, *1*, 77–83. [CrossRef]
66. Bundy, L.G.; Andraski, T.W. Recovery of fertilizer nitrogen in crop residues and cover crops on an irrigated sandy soil. *Soil Sci. Soc. Am. J.* **2005**, *69*, 640–648. [CrossRef]
67. Wang, G.L.; Chen, X.P.; Cui, Z.L.; Yue, S.C.; Zhang, F.S. Estimated reactive nitrogen losses for intensive maize production in China. *Agric. Ecosyst. Environ.* **2014**, *197*, 293–300. [CrossRef]
68. Ju, X.T.; Pan, J.R.; Liu, X.J.; Zhang, F.S. Study on the fate of nitrogen fertilizer in winter whet/sorghum rotation system in Bei jing suburban. *Plant Nutr. Fertil. Sci.* **2003**, *9*, 264–270. [CrossRef]
69. Fan, J.; Hao, M.D. Nitrate accumulation in soil profile of dryland farmland. *J. Agro-Environ. Sci.* **2003**, *22*, 263–266. (In Chinese) [CrossRef]
70. Corderio, C.F.D.S.; Rodrigues, D.R.; Rorator, A.F.D.S.; Echer, F.R. Cover crops and controlled-release urea decresse nitrogen mobility and improve nitrogen stock in a tropical sandy soil with cotton cultivation. *Rev. Bras. Cienc. Solo* **2022**, *46*, e0210113. [CrossRef]
71. Ju, X.; Liu, X.J.; Zhang, F.S.; Roelcke, M. Nitrogen fertilization, soil nitrate accumulation, and policy recommendations in several agricultural regions of China. *Ambio* **2004**, *33*, 300–305. [CrossRef] [PubMed]
72. Zhang, X.; Davidson, E.A.; Mauzerall, D.L.; Searchinger, T.D.; Dumas, P.; Shen, Y. Managing nitrogen for sustainable development. *Nature* **2015**, *528*, 51–59. [CrossRef] [PubMed]
73. Yao, Z.; Zhang, W.S.; Wang, X.B.; Zhang, W.; Liu, D.Y.; Chen, X.P. Agronomic, environmental, and ecosystem economic benefits of controlled-release nitrogen fertilizers for maize production in Southwest China. *J. Clean. Prod.* **2021**, *312*, 127611. [CrossRef]