

RESEARCH ON WATER AND NITROGEN MONITORING AND DECISION-MAKING TECHNOLOGY OF CHILI BASED ON UAV HYPERSPECTRAL REMOTE SENSING

RECHERCHE SUR LES TECHNOLOGIES DE SUIVI ET D'AIDE À LA DÉCISION POUR LA GESTION DE L'EAU ET DE L'AZOTE DU PIMENT FONDÉES SUR LA TÉLÉDÉTECTION HYPERSPECTRALE PAR DRONE

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ABSTRACT

Guizhou Province is one of the most important chili production bases in China, and chili cultivation plays an irreplaceable role in promoting local agricultural development, increasing farmers' income, and supporting rural revitalization. However, traditional irrigation and nitrogen fertilization management in chili production still heavily depends on empirical operation, which often leads to excessive or unreasonable water and fertilizer input, low water and nitrogen use efficiency, and even potential risks of soil degradation and non-point source pollution. Therefore, developing rapid, non-destructive, and large-scale monitoring and decision-making technologies is of great practical significance for the high-quality and green development of chili cultivation. Unmanned aerial vehicle (UAV) hyperspectral remote sensing, with its advantages of high efficiency, high spatial resolution, and real-time performance, provides a promising approach for water and nitrogen monitoring and decision-making in chili cultivation. In this study, field experiments were conducted in Liupanshui, Guizhou province, with different irrigation and nitrogen fertilization treatments. Three irrigation levels (low, medium and high) were performed with irrigation upper limits respectively at 50%, 65%, and 80% of field water capacity. Nitrogen fertilization was classified as low nitrogen (0, 50, 100 kg·hm⁻²), medium nitrogen (200, 250, 300 kg·hm⁻²), and high nitrogen (400, 500 kg·hm⁻²). During the growing season, the total nitrogen content (TN) and dry matter (DM) of chili, and the soil moisture content (SMC) were measured periodically. Hyperspectral images were synchronously obtained using an M350 RTK UAV equipped with an LR1601-IRIS hyperspectral camera. The results showed that TN and DM of chili responded differently to nitrogen application. With the increase in nitrogen application amount, TN increased continuously, while DM at the seedling stage increased under low nitrogen condition and decreased under high nitrogen condition. In addition, water-nitrogen coupling improved nitrogen use efficiency of chili. The suitable water-nitrogen regimes were medium water with low/medium nitrogen at the seedling stage, medium water with medium nitrogen at the early flowering stage and the early fruiting stage. The most sensitive vegetation indices for SMC were 2RVI2 and EVI, and the index for TN was DVI. By integrating the most sensitive spectral bands and vegetation indices, machine learning-based monitoring models of SMC and TN of chili were constructed, with coefficients of determination of 0.758 and 0.879, respectively. The critical nitrogen content curve of chili was calibrated based on the experimental data, and the nitrogen nutrition index (NNI) was proposed to evaluate nitrogen status of chili during cultivation. When NNI equals 0, it indicates that the nitrogen nutrition level of chili is at an optimal state; when NNI is less than 0, it signifies nitrogen deficiency in chili; when NNI is greater than 0, it denotes nitrogen excess in chili. A nitrogen deficit prediction model was further developed with a high coefficient of determination of 0.928. The models proposed in this study could rapidly obtain soil moisture and nitrogen deficit information from UAV hyperspectral images, providing theoretical and

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technical support for dynamic monitoring, rapid diagnosis, and precise decision-making of water and nitrogen management for chili at the field scale, and thus effectively improving water and nitrogen use efficiency in chili cultivation.

Keywords: Chili; UAV hyperspectral remote sensing; Water-nitrogen monitoring; Nitrogen deficit.

RÉSUMÉ

La province du Guizhou est l'une des principales régions productrices de piments en Chine, et la culture du piment joue un rôle irremplaçable dans la promotion du développement agricole local, l'augmentation des revenus des agriculteurs et la revitalisation rurale. Toutefois, la gestion traditionnelle de l'irrigation et de la fertilisation azotée repose encore largement sur l'expérience, ce qui entraîne souvent des apports excessifs ou inadaptés en eau et en engrais, une faible efficacité d'utilisation de l'eau et de l'azote, voire des risques de dégradation des sols et de pollution diffuse. Le développement de technologies rapides, non destructives et applicables à grande échelle pour le suivi et l'aide à la décision revêt donc une grande importance pratique pour une production de piments durable et de qualité. Grâce à sa grande efficacité, à sa haute résolution spatiale et à ses capacités en temps réel, la télédétection hyperspectrale par véhicule aérien sans pilote (UAV) constitue une approche prometteuse pour le suivi de l'eau et de l'azote et l'aide à la décision en culture du piment. Dans cette étude, des essais au champ comportant différents traitements d'irrigation et de fertilisation azotée ont été menés à Liupanshui, dans la province du Guizhou. Trois niveaux d'irrigation (faible, moyen et élevé) ont été appliqués, avec des limites supérieures respectives de 50 %, 65 % et 80 % de la capacité au champ. La fertilisation azotée a été répartie en trois catégories : faible (0, 50 et 100 kg·hm⁻²), moyenne (200, 250 et 300 kg·hm⁻²) et élevée (400 et 500 kg·hm⁻²). Pendant la période de végétation, la teneur totale en azote (TN) et la matière sèche (DM) du piment, ainsi que la teneur en eau du sol (SMC), ont été mesurées périodiquement. Des images hyperspectrales ont été acquises simultanément au moyen d'un UAV M350 RTK équipé d'une caméra hyperspectrale LR1601-IRIS. Les résultats ont montré que la TN et la DM du piment réagissaient différemment à l'apport d'azote. À mesure que la dose d'azote augmentait, la TN progressait continuellement, tandis qu'au stade plantule, la DM augmentait sous faible apport d'azote et diminuait sous fort apport. En outre, l'interaction eau-azote a amélioré l'efficacité d'utilisation de l'azote par le piment. Les régimes eau-azote appropriés correspondaient à un niveau d'eau moyen associé à un apport d'azote faible ou moyen au stade plantule, puis à un niveau d'eau moyen associé à un apport d'azote moyen au début de la floraison et au début de la fructification. Les indices de végétation les plus sensibles à la SMC étaient 2RVI2 et EVI, tandis que DVI était le plus sensible à la TN. L'intégration des bandes spectrales et des indices de végétation les plus sensibles a permis de construire, par apprentissage automatique, des modèles de suivi de la SMC et de la TN du piment, avec des coefficients de détermination respectifs de 0,758 et 0,879. La courbe critique de teneur en azote du piment a été étalonnée à partir des données expérimentales, et l'indice de nutrition azotée (NNI) a été proposé pour évaluer l'état azoté du piment au cours de la culture. Une valeur de NNI égale à 0 indique un niveau optimal de nutrition azotée ; une valeur inférieure à 0 traduit une carence en azote, tandis qu'une valeur supérieure à 0 indique un excès d'azote. Un modèle de prévision du déficit azoté a ensuite été mis au point, avec un coefficient de détermination élevé de 0,928. Les modèles proposés dans cette étude permettent d'obtenir rapidement, à partir d'images hyperspectrales acquises par UAV, des informations sur l'humidité du sol et le déficit azoté. Ils apportent ainsi un appui théorique et technique au suivi dynamique, au diagnostic rapide et à la prise de décision précise pour la gestion de l'eau et de l'azote du piment à l'échelle de la parcelle, améliorant ainsi efficacement l'efficacité d'utilisation de ces deux ressources.

Mots clés : Chili; Télédétection hyperspectrale acquise par UAV; Surveillance de l'eau et de l'azote; Déficit en azote.

1. Introduction

Chili is an important cash crop in China. Guizhou is one of the country's major chili-producing regions. However, current water and fertilizer management in local chili production remains extensive ^[1], with the water and nitrogen use efficiency far failing to meet the standard of precision agriculture in China. Nitrogen deficiency leads to a decline in chili yield, while nitrogen surplus not only wastes fertilizer resources and induces nitrite and ammonia toxicity in crops ^[2,3], but also causes soil and water pollution.

Traditionally, the water status of chili is mostly obtained indirectly through field soil moisture measurement, which is constrained by high costs and difficult maintenance of equipment. Crop nitrogen content is mainly determined by laboratory chemical analysis, which is time-consuming, labor-intensive, and poor in timeliness. Spectral technology has been widely applied in macroscopic agricultural monitoring, including planting area extraction, crop type classification, soil moisture inversion and nitrogen content estimation ^[4-7]. Equipped with spectral sensors, unmanned aerial vehicles (UAVs) can rapidly acquire remote sensing data in real time, achieving refined monitoring of crop growth and nutrient status. Obtaining soil moisture and crop nitrogen content via remote sensing is an important prerequisite for implementing precision irrigation and fertilization. Previous studies have made preliminary attempts to evaluate water-nitrogen status of vegetable using UAV remote sensing ^[8]. Nevertheless, in-depth research is still required on selecting sensitive canopy spectra of chili and estimating plant water-nitrogen status based on remote sensing information.

Moreover, limited attention has been paid to developing water and nitrogen management decision-making methods with UAV remote sensing data.

In this study, field experiments on chili were carried out, and low-altitude hyperspectral reflectance images were collected using a UAV-borne hyperspectral sensor. Combined with field sampling data, a remote sensing-based monitoring model for chili water and nitrogen status was constructed, and corresponding water-nitrogen decision-making methods were proposed. The findings provide technical support for improving regional water and nitrogen use efficiency in chili cultivation.

2. Materials and methods

2.1 Experimental site

The experiment was conducted at the experimental site in Dongfeng Village, Liupanshui City, Guizhou Province (26°12'N, 105°25'E) in 2024. The region has a typical subtropical monsoon climate with abundant annual precipitation ranging from 1200 to 1500 mm, presenting an obvious alternating pattern of dry and wet seasons ^[9]. The properties of the experimental soil are listed in Table 1.

Table 1 The properties of the experimental soil

Property	Value
type	yellow clayey soil
field capacity	36.4%
organic matter content	40.4 g kg ⁻¹
pH	6.88
total nitrogen	3.5 g kg ⁻¹
total phosphorus	0.72 g kg ⁻¹
total potassium	20.56 g kg ⁻¹
available nitrogen content	0.12 g kg ⁻¹
available phosphorus content	0.02 g kg ⁻¹
available potassium content	0.34 g kg ⁻¹

2.2. Experimental treatment

Layan 102, which is the widely cultivated chili in Guizhou Province ^[10], was used in the experiment. A total of 24 treatments were designed with different irrigation and fertilization levels, as shown in Table 2. Three irrigation levels were set: low irrigation (I₀) with the upper irrigation limit controlled at 50% of field capacity; moderate irrigation (I₁) at 65% of field capacity; and high irrigation (I₂) at 80% of field capacity. According to previous studies ^[11], eight nitrogen fertilization gradients were set. The pure nitrogen application was divided into low nitrogen (N₀: 0, N₁: 50, N₂: 100 kg·hm⁻²), moderate nitrogen (N₃: 200, N₄: 250, N₅: 300 kg·hm⁻²), and high nitrogen (N₆: 400, N₇: 500 kg·hm⁻²). Urea with a nitrogen content of 46% was adopted as the nitrogen fertilizer. The corresponding urea application rates were N₀: 0, N₁: 109, N₂: 217, N₃: 435, N₄: 543, N₅: 652, N₆: 870, N₇: 1086 kg·hm⁻². The application amounts of phosphate fertilizer and potassium fertilizer were fixed at 140 kg·hm⁻² (P₂O₅) and 200 kg·hm⁻² (K₂O), respectively.

Table 2 Experimental treatments

Treatments	Irrigation treatment (upper irrigation limit)	Fertilization treatment (46% urea)
1	I ₀ (50% field capacity)	N ₀ :0 kg/hm ²
2	I ₀ (50% field capacity)	N ₁ :109 kg/hm ²
3	I ₀ (50% field capacity)	N ₂ :217 kg/hm ²
4	I ₀ (50% field capacity)	N ₃ :435 kg/hm ²
5	I ₀ (50% field capacity)	N ₄ :543 kg/hm ²
6	I ₀ (50% field capacity)	N ₅ :652 kg/hm ²
7	I ₀ (50% field capacity)	N ₆ :870 kg/hm ²
8	I ₀ (50% field capacity)	N ₇ :1086 kg/hm ²
9	I ₁ (65% field capacity)	N ₀ :0 kg/hm ²
10	I ₁ (65% field capacity)	N ₁ :109 kg/hm ²
11	I ₁ (65% field capacity)	N ₂ :217 kg/hm ²
12	I ₁ (65% field capacity)	N ₃ :435 kg/hm ²
13	I ₁ (65% field capacity)	N ₄ :543 kg/hm ²
14	I ₁ (65% field capacity)	N ₅ :652 kg/hm ²
15	I ₁ (65% field capacity)	N ₆ :870 kg/hm ²
16	I ₁ (65% field capacity)	N ₇ :1086 kg/hm ²
17	I ₂ (80% field capacity)	N ₀ :0 kg/hm ²
18	I ₂ (80% field capacity)	N ₁ :109 kg/hm ²
19	I ₂ (80% field capacity)	N ₂ :217 kg/hm ²
20	I ₂ (80% field capacity)	N ₃ :435 kg/hm ²
21	I ₂ (80% field capacity)	N ₄ :543 kg/hm ²
22	I ₂ (80% field capacity)	N ₅ :652 kg/hm ²
23	I ₂ (80% field capacity)	N ₆ :870 kg/hm ²
24	I ₂ (80% field capacity)	N ₇ :1086 kg/hm ²

The experiment was conducted in 24 plots, corresponding to 24 treatments. Each plot was 1 m wide and 12 m long, with a chili plant spacing of 0.5 m. Two sampling zones were arranged in each plot, and three sampling points were set within each zone for the collection of canopy nitrogen content.

2.3 Data collection

1. Soil moisture content
2. In this study, embedded probes of the MiniTrase soil moisture monitoring system were used to constantly measure soil moisture content at a soil depth of 20 cm.
3. Spectral data
4. The UAV remote sensing monitoring system consists of a UAV platform (M350 RTK), a hyperspectral camera (LR1601-IRIS), an airborne spectral analysis system, and several accessories. A total of nine phases of data were collected throughout the experiment, including the seedling stage (May 31, June 7, June 14), initial flowering stage (July 8, July 15, July 22), and initial fruiting stage (August 8, August 23, August 29).
5. Nitrogen content of chili
6. The Kjeldahl method was adopted to determine the nitrogen content of chili. Before each spectral data acquisition, two chili plants were selected and marked for each treatment. The marked plants were sampled for measurement after UAV flight.
7. Dry matter of chili
8. Before each spectral data acquisition, two chili plants were selected and marked for each treatment. The marked plants were sampled for measurement after UAV flight. The samples were placed in a vacuum drying device and treated under specific vacuum and heating conditions until the sample mass remained constant. The dry matter weight was then measured.

3 Results and Discussion

3.1 Effects of fertilization treatments on total nitrogen and dry matter accumulation of chili

At the seedling stage of chili, the total nitrogen content showed an increasing trend with the rise of nitrogen application rate (Figure 1). By contrast, the dry matter content of chili decreased as nitrogen fertilizer input increased, indicating that excessive nitrogen application inhibited dry matter accumulation, and the treatments with low or medium nitrogen application rates (50–200 kg/hm²) were more conducive to dry matter accumulation. At the initial flowering and initial fruiting stages, both total nitrogen content and dry matter content of chili increased significantly with increasing nitrogen application rates (Figure 2 and 3), suggesting that sufficient nitrogen supply remarkably promoted dry matter accumulation. However, at the initial fruiting stage, as the nitrogen application rate increased, the increment in dry matter gradually diminished, and dry matter accumulation exhibited considerable fluctuations.

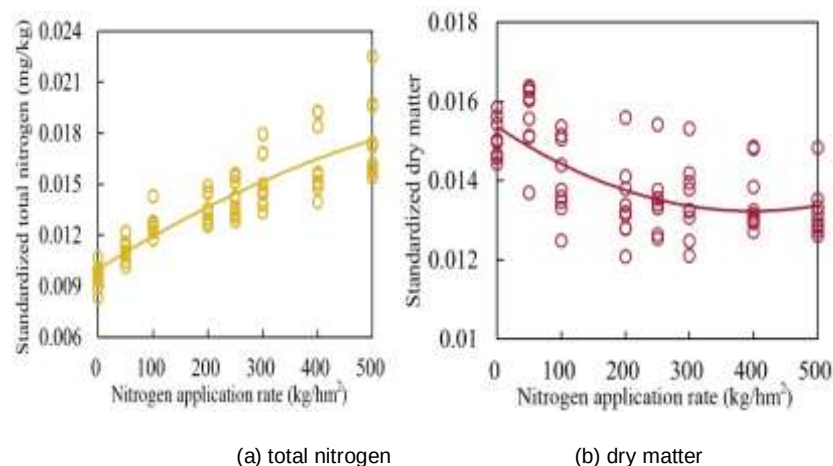


Figure 1. Changes in total nitrogen and dry matter content of chili with nitrogen application rate at the seedling stage

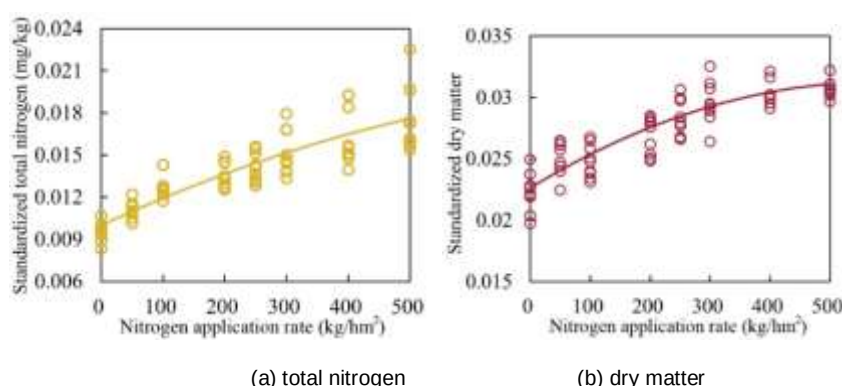


Figure 2. Changes in total nitrogen and dry matter content of chili with nitrogen application rate at the initial flowering stage

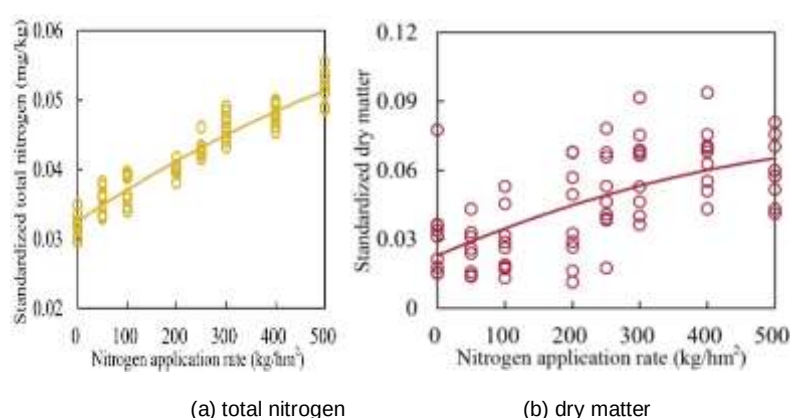


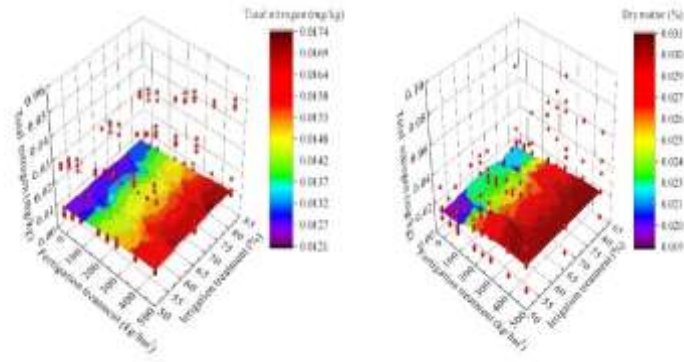
Figure 3. Changes in total nitrogen and dry matter content of chili with nitrogen application rate at the initial fruiting stage

3.2 Effects of water-nitrogen coupling on total nitrogen and dry matter accumulation of chili

The interaction relationship of chili total nitrogen, dry matter accumulation and different water-nitrogen treatments are shown in Figure 4, Table 3 and Table 4. At the seedling stage of chili, under medium water treatment (irrigation upper limit of 65% field capacity) and low to medium nitrogen treatment (50–200 kg/hm²), the proportion of total nitrogen content falling in the medium to high value range ([0.015, 0.019]) was 38.5%. Under medium to high water treatment (irrigation upper limit of 65% and 80% field capacity) combined with low to medium nitrogen treatments (nitrogen application rate of 50–200 kg/hm²), the proportion of dry matter in the high-value range reached 43.8%–75%. The above results indicated that the optimal water-nitrogen treatment for chili at the seedling stage was medium water with low/medium nitrogen.

At the initial flowering stage, under medium water treatment (irrigation upper limit of 65% field capacity), the proportion of total nitrogen content in the high value range ([0.015, 0.017]) was 35.3%. When the nitrogen application rate exceeded 300 kg/hm², the accumulation of total nitrogen content accelerated with medium to high water treatments. Besides, the dry matter content increased with the rise of nitrogen application rate. The above results suggested that the suitable water-nitrogen combination for chili at the initial flowering stage was medium water with medium nitrogen.

At the initial fruiting stage, under medium water treatment (irrigation upper limit 65% field capacity), the proportion of total nitrogen in the highest value range ([0.049, 0.055]) reached 50%, and the proportion of dry matter in the highest value range ([0.073, 0.094]) was 57.1%. Besides, it was observed that the positive effect of nitrogen application rate on total nitrogen accumulation peaked at approximately 300 kg/hm². This demonstrated that the optimal water-nitrogen treatment for chili at the initial fruiting stage was medium water with medium nitrogen.



(a) total nitrogen

(b) dry matter

Figure 4. Variation of total nitrogen and dry matter of chili under different treatments

Table 3. Distribution of total nitrogen samples under various irrigation levels at key growth stages of chili

Key growth stages	Standardized total nitrogen	Irrigation treatments			Total samples
		50% field capacity	65% field capacity	80% field capacity	
Seedling stage	[0.008,0.012]	7(38.9%)	5(27.8%)	6(33.3%)	18
	[0.012,0.015]	13(36.1%)	12(33.3%)	11(30.6%)	36
	[0.015,0.019]	3(23.1%)	5(38.5%)	5(38.5%)	13
	[0.019,0.023]	1(20%)	2(40%)	2(40%)	5
Total samples		24	24	24	72
Initial flowering stage	[0.01,0.012]	2(50%)	1(25%)	1(25%)	4
	[0.012,0.013]	6(33.3%)	5(27.8%)	7(38.9%)	18
	[0.013,0.015]	11(33.3%)	12(36.4%)	10(30.3%)	33
	[0.015,0.017]	5(29.4%)	6(35.3%)	6(35.3%)	17
Total samples		24	24	24	72
Initial fruiting stage	[0.03,0.036]	6(33.3%)	6(33.3%)	6(33.3%)	18
	[0.036,0.043]	8(36.4%)	7(31.8%)	7(31.8%)	22
	[0.043,0.049]	8(36.4%)	6(27.3%)	8(36.4%)	22
	[0.049,0.055]	2(20%)	5(50%)	3(30%)	10
Total samples		24	24	24	72

Table 4. Distribution of dry matter samples under various irrigation levels at key growth stages of chili

Key growth stages	Standardized dry matter	Irrigation treatments			Total samples
		50% field capacity	65% field capacity	80% field capacity	
Seedling stage	[0.012,0.013]	13(37.143%)	11(31.4%)	11(31.4%)	35
	[0.013,0.015]	7(41.176%)	3(17.6%)	7(41.2%)	17
	[0.015,0.016]	4(25%)	7(43.8%)	5(31.2%)	16
	[0.016,0.017]	0(0%)	3(75%)	1(25%)	4

Key growth stages	Standardized dry matter	Irrigation treatments			Total samples
		50% field capacity	65% field capacity	80% field capacity	
Total samples		24	24	24	72
Initial flowering stage	[0.01,0.012)	2(50%)	1(25%)	1(25%)	4
	[0.012,0.013)	6(33.333%)	5(27.778%)	7(38.889%)	18
	[0.013,0.015)	11(33.333%)	12(36.364%)	10(30.303%)	33
	[0.015,0.017]	5(29.412%)	6(35.294%)	6(35.294%)	17
Total samples		24	24	24	72
Initial fruiting stage	[0.011,0.032)	10(35.714%)	7(25%)	11(39.286%)	28
	[0.032,0.052)	8(38.095%)	8(38.095%)	5(23.81%)	21
	[0.052,0.073)	6(37.5%)	5(31.25%)	5(31.25%)	16
	[0.073,0.094]	0(0%)	4(57.143%)	3(42.857%)	7
Total samples		24	24	24	72

3.3 Selection of sensitive factors for soil moisture content and chili total nitrogen

The correlation coefficients of vegetation indices DVI, EVI and 2RVI2 with soil water content in chili fields were -0.302, -0.387 and -0.357, respectively, showing a significant positive correlation ($P < 0.1$), among which EVI and 2RVI2 were the most significant sensitive factors. The correlation coefficients of vegetation indices EVI, DVI and 2RVI2 with chili total nitrogen were 0.413, 0.465 and 0.405, all presenting an extremely significant positive correlation ($P < 0.01$). DVI was the most prominent sensitive factor. The distribution characteristics of spectral bands sensitive to soil moisture content are shown in Table 5. Among the sensitive spectral bands, B5 (400.8780 nm), B128 (926.6640 nm), B1 (384.6180 nm) and B33 (516.1770 nm) exhibited the strongest characteristics, accounting for 13.3% of the total bands.

Table 5 Distribution of sensitive spectral bands for soil moisture content in chili field

Spectral band	Feature Importance	Spectral band	Feature Importance	Spectral band	Feature Importance	Spectral band	Feature Importance
B5	4.70%	B12	1.70%	B72	1.30%	B117	1.10%
B128	3.20%	B29	1.70%	B31	1.20%	B14	1.00%
B1	2.70%	B67	1.60%	B70	1.20%	B69	1.00%
B33	2.70%	B79	1.60%	B71	1.20%	B80	1.00%
B122	2.10%	B125	1.60%	B126	1.20%	B20	0.90%
B2	2.00%	B15	1.50%	B8	1.10%	B23	0.90%
B3	1.90%	B26	1.40%	B44	1.10%	B83	0.90%
B4	1.80%	B90	1.40%	B77	1.10%	B120	0.90%
B6	1.70%	B65	1.30%	B81	1.10%	B7	0.80%

The distribution characteristics of spectral bands sensitive to chili total nitrogen are shown in Table 6. Among the sensitive spectral bands, B83 (728.5080nm), B40 (545.4060nm), B127(922.1880nm) and B96 (785.0660nm) exhibited the strongest characteristics, accounting for 22.5% of the total bands.

Table 6 Distribution of sensitive spectral bands for total nitrogen of chili

Spectral band	Feature Importance	Spectral band	Feature Importance	Spectral band	Feature Importance	Spectral band	Feature Importance
B83	5.80%	B88	3.60%	B55	1.90%	B110	1.90%
B40	5.60%	B2	2.00%	B69	1.90%	B111	1.90%
B127	5.60%	B50	2.00%	B86	1.90%	B116	1.90%
B96	5.50%	B128	2.00%	B89	1.90%	B120	1.90%
B76	3.90%	B12	1.90%	B93	1.90%	B19	1.80%
B78	3.80%	B17	1.90%	B99	1.90%	B41	1.80%
B90	3.80%	B43	1.90%	B103	1.90%	B49	1.80%
B47	3.70%	B51	1.90%	B104	1.90%	B62	1.80%
B122	3.70%	B53	1.90%	B105	1.90%	B108	1.80%

3.4 Monitoring model of soil moisture content and chili nitrogen content

The sensitive vegetation indices and sensitive spectral bands of soil moisture content were filtered to construct feature space vectors. The CatBoost algorithm was adopted for soil moisture content inversion. The results showed that the CatBoost model achieved good performance, with the coefficient of determination reaching 0.758 on the test data set (Figure 5), indicating that the model could effectively monitor the variation of soil moisture content.

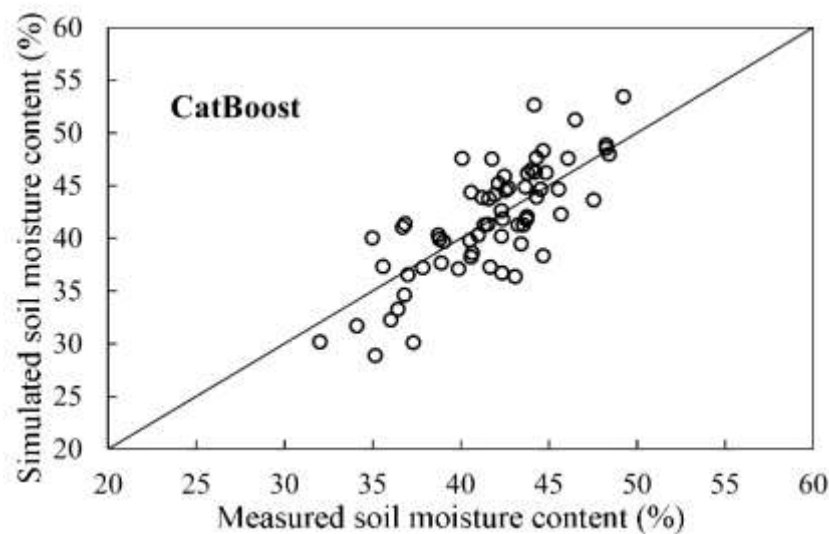


Figure 5. Comparison of simulated and measured soil moisture content

Similarly, taking sensitive vegetation indices and spectral bands as the feature space vector of the Random Forest (RF) model, the model performed well in estimating chili nitrogen content, with the coefficient of determination up to 0.879 on the test set (Figure 6).

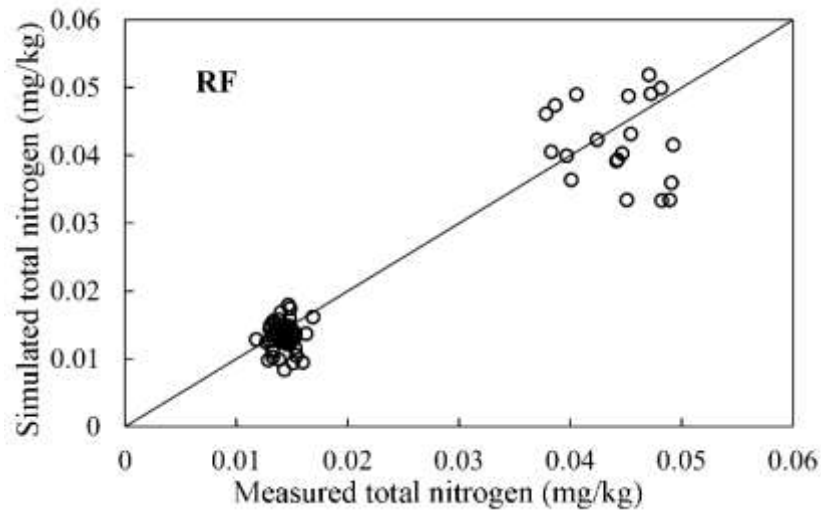


Figure 6. Comparison of simulated and measured total nitrogen of chili

3.5 Prediction model of chili nitrogen deficit

Critical nitrogen content is the minimum nitrogen concentration required for crops to reach the maximum dry matter. The critical nitrogen content curve reflects the relationship between crop nitrogen content and plant dry matter accumulation [12]. The power function was used to fit the data of critical nitrogen content and dry matter of chili at each sampling stage, and the critical nitrogen content curve of chili was thereby derived (Figure 7).

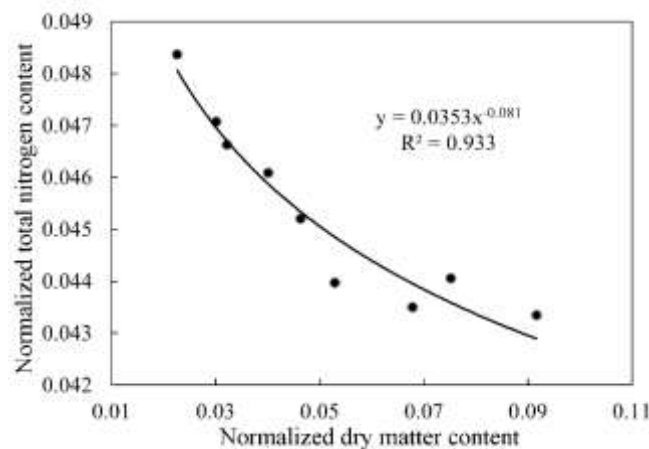


Figure 7. Critical nitrogen content curve of chili

The total nitrogen nutrition index (NNI) was established as an indicator for qualitative diagnosis of chili nitrogen status, and the calculation formula is as follows:

$$NNI = N_i - N_c \quad (1)$$

where N_i is the actual total nitrogen content of chili, N_c is the critical total nitrogen content. $NNI = 0$ means the nitrogen nutrition level of chili is optimal; $NNI < 0$ indicates nitrogen deficiency and fertilizer application is needed; $NNI > 0$ means nitrogen excess and fertilizer application should be reduced.

Based on the critical nitrogen content curve of chili, the relationship between the critical total nitrogen content N_c and the actual total nitrogen content N_i of experiment was calculated, and then the total nitrogen nutrition index of chili was deduced (Figure 8). It is observed that the total nitrogen nutrition index of chili exhibits an upward trend with the increase of nitrogen application rate. When the nitrogen application rate reached 306 kg/hm², the nitrogen nutrition of chili reached the optimal balanced level, and the increasing rate of the index began to slow down, indicating that this application rate was close to the threshold for meeting the maximum nitrogen demand of chili. As the nitrogen application rate further increased to 500 kg/hm², NNI reached its peak with an obviously stable growth trend. Although excessive nitrogen fertilizer could further promote NNI , it was accompanied by diminishing marginal benefits.

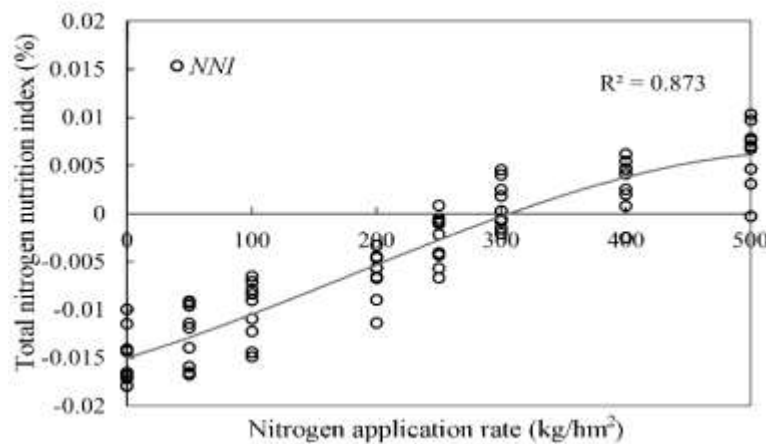


Figure 8. Characteristic of total nitrogen nutrition index of chili

To achieve quantitative evaluation of nitrogen status of chili, a quantitative diagnosis model of nitrogen deficit amount was established. With the employment of the K-nearest Neighbor (KNN) algorithm, the inverted total nitrogen content and the total nitrogen nutrition index were combined as input variables to predict nitrogen deficit. The results showed that the model could precisely predict the nitrogen deficit amount, with the coefficient of determination R^2 of 0.928 on the test set (Figure 9).

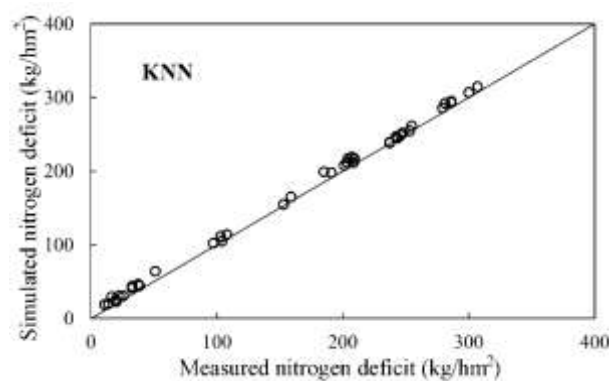


Figure 9. Comparison of simulated and measured nitrogen deficit amount

4. Conclusion

With the increasing nitrogen application rate, the total nitrogen content of chili showed an upward trend throughout the key growth stages. For dry matter content, obvious high-nitrogen inhibition effect existed at the seedling stage. Medium water combined with low/moderate nitrogen was suitable for the

seedling stage, while medium water combined with medium nitrogen was applicable for the initial flowering and initial fruiting stages.

EVI and 2RVI2 were the vegetation indices most sensitive to soil moisture content, and DVI was the most sensitive to chili nitrogen status. Taking sensitive spectral bands and sensitive vegetation indices as input variables, monitoring models of soil moisture and chili nitrogen based on machine learning algorithms were established with the coefficient of determination of 0.758 and 0.879, respectively.

The total nitrogen nutrition index of chili was established based on the critical nitrogen content curve to quantify the threshold of chili nitrogen deficit. Taking total nitrogen content and the total nitrogen nutrition index as input variables, a prediction model for chili nitrogen fertilizer deficit was developed, with the coefficient of determination up to 0.928.

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