

DOI: 10.3724/SP.J.1006.2026.53064

不同密度下氮肥运筹对半干旱区青贮玉米碳氮积累与转运特征的影响

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摘 要: 明确不同密度下氮肥运筹对半干旱区青贮玉米碳氮积累、转运及粗蛋白合成的影响, 可为半干旱区青贮玉米高产优质栽培提供理论依据。本研究以“陇青贮 1 号”为研究对象, 设计 2 种密度(6.0 万株 hm^{-2} 和 7.5 万株 hm^{-2}), 3 种施肥方式(氮肥全部基施、40%和 60%氮肥大喇叭口期追施), 测定了青贮玉米花前和花后干物质、非结构性碳水化合物(NSC)和氮素积累量、转运量和贡献率, 并分析了上述指标与青贮玉米产量、粗蛋白含量和产量之间的相关关系。结果表明, 氮肥追施可显著降低花前干物质和 NSC 积累与转运, 但提高花后干物质和 NSC 积累量。其中, 与 CK1 (6.0 万株 hm^{-2} , 氮肥全部基施)相比, T1 (6.0 万株 hm^{-2} , 40%氮肥大喇叭口期追施)和 T2 (6.0 万株 hm^{-2} , 60%氮肥大喇叭口期追施)花前干物质和 NSC 的转运量、转运率及其对干物质贡献率均显著降低, 但花后干物质积累量分别平均提高 46.29%和 22.63%, 花后 NSC 积累量分别平均提高 29.53%和 17.54%, 均差异显著; 与 CK2 (7.5 万株 hm^{-2} , 氮肥全部基施)相比, T3 (7.5 万株 hm^{-2} , 40%氮肥大喇叭口期追施)和 T4 (7.5 万株 hm^{-2} , 60%氮肥大喇叭口期追施)花前干物质和 NSC 的转运量、转运率及其对干物质贡献率均显著降低, 但花后干物质积累量分别平均提高 5.88%和 5.90%, 花后 NSC 积累量分别平均提高 19.53%和 65.57%, 均差异显著。氮肥追施可显著提高花前氮素转运量、转运率和花后氮素积累量, 其中, 与 CK1 相比, T1 花前氮素转运量、转运率和花后氮素积累量分别平均提高 64.48%、7.77%和 74.86%, T2 分别平均提高 43.21%、7.52%和 32.27%; 与 CK2 相比, T3 分别平均提高 12.51%、8.92%和 74.94%, T4 分别平均提高 47.37%、8.75%和 73.41%。青贮玉米产量与花后干物质积累量($R^2 = 0.1547^*$)、花后氮素积累量($R^2 = 0.1582^*$)呈显著正相关, 粗蛋白含量与花前氮素转运量($R^2 = 0.1263^*$)、花后氮素积累量($R^2 = 0.1764^{**}$)、花后 NSC 积累量($R^2 = 0.2155^{**}$)呈正相关, 粗蛋白产量与花后干物质积累量($R^2 = 0.1723^*$)、花后氮素积累量($R^2 = 0.1682^*$)呈显著正相关。氮肥追施在提高花前氮素转运和花后碳氮积累量的前提下, 显著促进了青贮玉米粗蛋白合成, 其中, T1 粗蛋白含量 9.42%, T2 粗蛋白含量 8.40%, 分别较 CK1 提高 62.18%、44.80%; T3 粗蛋白含量 7.06%, T4 粗蛋白含量 8.12%, 分别较 CK2 提高 39.25%、60.15%。因此, T1 和 T4 是该区适宜推广应用的青贮玉米品质提升种植方式。

关键词: 密度; 施肥; 调控; 碳氮积累; 粗蛋白合成

Effects of nitrogen application at different densities on carbon and nitrogen accumulation and translocation characteristics in forage maize in semi-arid regions

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本研究由国家自然科学基金项目(32360532), 甘肃省自然科学基金重点项目(23JRRA1335), 农业农村部西北旱地农业绿色低碳重点实验室和甘肃省旱作区水资源高效利用重点实验室开放基金(2024HNS12)资助。

This study was supported by the National Natural Science Foundation of China (32360532), the Key Project of the Gansu Provincial Natural Science Foundation (23JRRA1335), the Open Fund of the Key Laboratory of Northwest Dryland Agriculture Green and Low-Carbon, Ministry of Agriculture and Rural Affairs, and the Open Fund of the Key Laboratory of Water Resources Efficient Utilization in Arid Areas of Gansu Province (2024HNS12).

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Received (收稿日期): 2025-08-20; Accepted (接受日期): 2026-01-22; Published online (网络出版日期): 2026-02-05.

URL: <https://link.cnki.net/urlid/11.1809.S.20260205.1002.004>

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Abstract: To provide a theoretical basis for high-yield and high-quality cultivation of silage maize in semi-arid regions, this study investigated the effects of nitrogen application on carbon and nitrogen accumulation, translocation, and crude protein synthesis in silage maize under different planting densities. Using ‘Longqingzhu 1’ as the experimental material, two planting densities (60,000 and 75,000 plants hm^{-2}) and three nitrogen application regimes (all nitrogen as basal fertilizer, 40% and 60% of nitrogen applied as topdressing at the bell stage) were examined. Measurements included dry matter, non-structural carbohydrate (NSC), and nitrogen accumulation and translocation before and after flowering, as well as their contribution to total plant biomass. Correlations between these physiological parameters and forage yield, crude protein content, and crude protein yield were also analyzed. Compared with CK1 (60,000 plants hm^{-2} with all nitrogen applied basally), treatments T1 and T2 (same density with 40% and 60% nitrogen topdressing, respectively) showed significantly reduced dry matter and NSC translocation and contribution rates at the pre-flowering stage, but significantly increased post-flowering dry matter accumulation by 46.29% and 22.63%, and NSC accumulation by 29.53% and 17.54%, respectively. Compared with CK2 (75,000 plants hm^{-2} with all nitrogen applied basally), T3 and T4 (same density with 40% and 60% nitrogen topdressing, respectively) also showed reduced translocation and contribution rates at the pre-flowering stage, while post-flowering dry matter increased by 5.88% and 5.90%, and NSC accumulation increased by 19.53% and 65.57%, respectively. Nitrogen topdressing significantly increased nitrogen translocation and translocation rate at the pre-flowering stage, as well as nitrogen accumulation at the post-flowering stage. Compared with CK1, T1 showed increases of 64.48%, 7.77%, and 74.86%, while T2 increased by 43.21%, 7.52%, and 32.27%, respectively. Compared with CK2, T3 increased by 12.51%, 8.92%, and 74.94%, and T4 by 47.37%, 8.75%, and 73.41%, respectively. Forage yield was significantly positively correlated with post-flowering dry matter accumulation ($R^2 = 0.1547^*$) and nitrogen accumulation ($R^2 = 0.1582^*$). Crude protein content was positively correlated with pre-flowering nitrogen translocation ($R^2 = 0.1263^*$), post-flowering nitrogen accumulation ($R^2 = 0.1764^{**}$), and NSC accumulation ($R^2 = 0.2155^{**}$). The crude protein yield of the whole plant was significantly positively correlated with post-flowering dry matter ($R^2 = 0.1723^*$) and nitrogen accumulation ($R^2 = 0.1682^*$). These results indicate that nitrogen topdressing significantly promotes crude protein synthesis in silage maize by enhancing nitrogen translocation at the pre-flowering stage and carbon and nitrogen accumulation at the post-flowering stage. The crude protein content of T1 and T2 was 9.42% and 8.40%, which was 62.18% and 44.80% higher than that of CK1, respectively. The crude protein content of T3 and T4 was 7.06% and 8.12%, 39.25% and 60.15% higher than that of CK2, respectively. Therefore, T1 and T4 are recommended for improving silage maize quality in semi-arid regions.

Keywords: planting density; nitrogen fertilization; regulation; carbon and nitrogen accumulation; crude protein synthesis

随着我国人民生活水平的提高,对肉蛋奶产品的需求不断增大,饲料短缺愈发严重,饲料危机正威胁着我国粮食安全^[1],加快饲草业发展已成为确保我国粮食安全的必经之路^[2]。因此,2020 年中央一号文件中指出“以北方农牧交错带为重点扩大粮改饲规模”,2022 年农业农村部制定《“十四五”全国饲草产业发展规划》,以促进饲草产业和草食畜牧业高质量发展,但截至 2023 年 12 月,牧业饲草行业分析报告显示,我国饲草,尤其是优质饲草缺口巨大,达 4000 万吨以上。在我国耕地有限的现实下,如何增加优质饲草供应,减少牛羊养殖精饲料用量成为饲草业和养殖业高质量发展的瓶颈。西北黄土高原旱作区是粮改饲重点区域,青贮玉米作为该区主要的饲料来源,近年来种植面积逐年增加,但粗蛋白含量多年徘徊在 3%~5%^[3],与《饲草营养品质评定 GI 法(GB/T 23387-2009)》规定的奶牛和绵羊一级饲草粗蛋白含量 17%~19%相差甚远。究其原因,主要是饲草品质调控机制研究薄弱,种植密度和施肥随

意导致的饲草玉米产量和品质调控途径缺乏。

植株碳氮代谢与粗蛋白合成共同构成植物生长发育和产量形成的重要基础^[4]。碳氮代谢是植物体内碳和氮元素吸收、转化、利用及分配的过程,而粗蛋白则是氮素代谢的重要产物之一,直接关系到植物体内蛋白质的含量和功能^[5-6]。在水稻研究中,高氮水平显著提高了稻米的蛋白含量^[7]。此外,关键酶和基因表达在调控碳氮代谢和蛋白质合成中起重要作用,14-3-3 蛋白在植物碳氮代谢中的调控作用显著影响氨基酸代谢和蛋白质合成^[8]。因此,通过优化氮肥管理和栽培技术,调节碳氮代谢平衡,可以提高作物的蛋白质含量和产量,为农业实践提供科学依据。

密度和施肥可显著影响植株碳氮代谢,进而影响作物产量,有效调节青贮玉米粗蛋白合成^[9-14]。青贮玉米品种的鲜草产量、株高、穗位高随密度的增加先升高后下降,单株产量、单穗重等农艺性状则逐渐下降^[15-17]。侯湃等^[18]研究指出,青贮玉米的品质与青贮玉米粗蛋白含量呈正相关。但也有研究表

明,随着密度的增加,青贮玉米的粗蛋白含量均逐渐下降^[17,19]。施肥对提高作物产量、品质和养分利用效率等至关重要,其中氮素是决定植物生产力的主要矿质元素之一^[20-21]。追施氮肥可以显著提高玉米中可溶性蛋白质含量,改善作物品质,从而有助于提升粗蛋白含量^[22]。当施氮量为 120、240 和 360 kg hm⁻² 时,饲草玉米粗蛋白含量较不施氮处理分别显著提升 24.1%、62.1%和 63.6%^[23]。但青贮玉米粗蛋白含量对施氮量的响应同样存在“度”的问题,即只有在一定施氮范围内,增施氮肥才表现为正效应。

目前,密度和施肥对青贮玉米粗蛋白合成调控机制方面已有研究,认为密度和施肥方式通过提高饲草玉米植株 N/K、叶片 GS 活性、茎秆 NR 和籽粒 GPT 活性并减缓 AA 含量下降而显著提高饲草玉米粗蛋白含量^[13],然而,密度和施肥因改变了土壤环境条件势必影响土壤水分供应和土壤碳氮代谢方式^[24-26],进而影响土壤养分供应和地上部粗蛋白合成,目前此方面

研究较少。因此,本研究以“陇青贮 1 号”为材料,通过设置不同密度和施肥处理,考察青贮玉米花前和花后干物质、氮素及 NSC 积累量和转运量,并分析青贮玉米花前和花后干物质、氮素及 NSC 积累和转运与青贮玉米粗蛋白含量的相关性,探明不同密度下施肥方式调控半干旱区青贮玉米花后碳氮积累与转运特征从而影响粗蛋白合成的机理,旨在为半干旱区青贮玉米高产优质栽培提供理论依据和技术支撑,为推动区域饲草玉米种植业绿色发展做出积极贡献。

1 材料与方法

1.1 试验区概况

本研究于 2023—2024 年在甘肃省农业科学院定西试验站(甘肃省定西市安定区团结镇唐家堡村)进行。该区属中温带半干旱气候,气候数据如图 1,海拔 1970 m,年平均气温 6.2℃,年辐射总量 5898 MJ m⁻²,年日照时数 2500 h,≥10℃积温 2075.1℃,无霜期

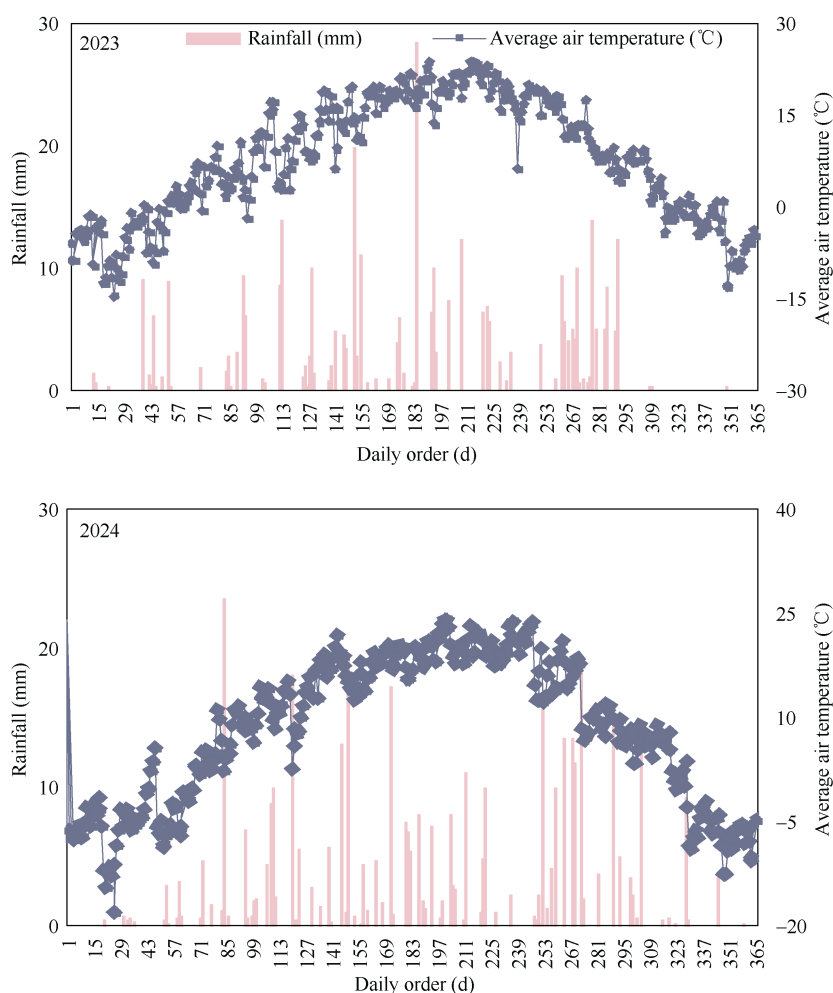


图 1 2023—2024 年试验区降雨量和平均气温

Fig. 1 Precipitation and average air temperature in the experimental area during 2023–2024

140 d, 作物一年一熟, 为典型旱作雨养农业区。年均降雨量 415 mm, 6—9 月降雨量占年降雨量的 68%, 降雨相对变率为 24%, 400 mm 降雨保证率为 48%。试验区土壤为黄绵土, 0~30 cm 土层平均容重 1.25 g m⁻³, 田间持水量 21.18%, 凋萎系数 7.2%。土壤含有机质 11.99 g kg⁻¹、全氮 1.16 g kg⁻¹、全磷 0.25 g kg⁻¹、全钾 17.3 g kg⁻¹、NH₄⁺-N 4.8 mg kg⁻¹、NO₃⁻-N 0.8 mg kg⁻¹、速效磷 8.67 mg kg⁻¹、速效钾 121.50 mg kg⁻¹, pH 8.35。

1.2 试验设计

以春玉米(*Zea mays*)为研究材料, 品种为‘陇青贮 1 号’(其饲用部位包括茎、叶、苞叶、穗轴和籽粒, 即玉米地上部分的所有器官)。采用单因素完全随机设计, 全部处理采用全膜双垄沟种植方式, 试

验小区面积 7 m×15 m = 105 m², 3 次重复, 施肥量为纯 N 300 kg hm⁻², P₂O₅ 150 kg hm⁻², K₂O 135 kg hm⁻², 其中, 氮肥使用尿素, 磷肥使用过磷酸钙, 钾肥使用硫酸钾, 且磷钾肥全部基施。设置 2 个密度(6.0 万株 hm⁻² 和 7.5 万株 hm⁻²), 3 种氮肥施肥方式(氮肥全部基施、40%和 60%氮肥大喇叭口期追施), 共 6 个处理(表 1)。试验中氮磷钾肥料为复合肥, 执行期间采用秋覆膜, 当年玉米收获后不揭膜, 翌年播种前在整好的农田用起垄器起双垄, 大垄宽 70 cm、高 10 cm, 小垄宽 40 cm、高 15 cm, 全地面地膜覆盖, 地膜厚度 8 mm; 玉米采用人工点播, 株距 30~40 cm, 每年 4 月 20 日前后用玉米点播器点播于垄沟中, 9 月 20 日前后(青贮玉米蜡熟期)收获。

表 1 试验处理与描述
Table 1 Experimental treatments and description

处理 Treatment	处理描述 Description of treatment
CK1	密度为 6.0 万株 hm ⁻² , 氮肥全部基施 Density of 60,000 plants hm ⁻² , all nitrogen fertilizer applied as basal dressing
T1	密度为 6.0 万株 hm ⁻² , 40%氮肥大喇叭口期追施 Density of 60,000 plants hm ⁻² , 40% nitrogen fertilizer topdressing at the bell stage
T2	密度为 6.0 万株 hm ⁻² , 60%氮肥大喇叭口期追施 Density of 60,000 plants hm ⁻² , 60% nitrogen fertilizer topdressing at the bell stage
CK2	密度为 7.5 万株 hm ⁻² , 氮肥全部基施 Density of 75,000 plants hm ⁻² , all nitrogen fertilizer applied as basal dressing
T3	密度为 7.5 万株 hm ⁻² , 40%氮肥大喇叭口期追施 Density of 75,000 plants hm ⁻² , 40% nitrogen fertilizer topdressing at the bell stage
T4	密度为 7.5 万株 hm ⁻² , 60%氮肥大喇叭口期追施 Density of 75,000 plants hm ⁻² , 60% nitrogen fertilizer topdressing at the bell stage

1.3 测定指标与方法

1.3.1 干物质积累与转运 2023—2024 年, 在吐丝期, 选择长势和吐丝期基本一致的植株挂牌标记。由于玉米的茎叶干重仍会在吐丝期后有一定增长, 直到吐丝 7 d 后才发生物质转运^[27], 因此于吐丝后 7 d、灌浆期和收获期, 每个小区分别选取挂牌植株 2 株, 将植株地上部分为叶片、茎秆和穗, 在 105℃下杀青 30 min 后 75℃烘至恒重后称重。用高速粉碎机将样品粉碎备用, 用于全氮、可溶性糖和淀粉含量的测定。并计算整株的花前干物质转运量(dry matter translocation amount of pre-silking in stem and leaf, DRA)、花前干物质转运率(dry matter translocation rate of pre-silking in stem and leaf, DRR, %)、花前干物质转运对干重产量的贡献率(contribution rate of dry matter translocation amount of pre-silking in stem and leaf, CDRA, %)、花后干物质积累量(dry matter accumulation amount of post-silking in stem

and leaf, DAA)等指标^[28], 计算公式如下:
DRA = 吐丝后 7 d 茎叶干重 - 成熟期茎叶干重(1)
DRR = 花前物质转运量/吐丝后 7 d 茎叶干重 × 100% (2)
CDRA = 花前干物质转运量/收获期饲草干重 × 100% (3)
DAA = 成熟期植株总干重 - 吐丝后 7 d 植株总干重 (4)

1.3.2 非结构性碳水化合物积累与转运测定

2023—2024 年, 取样方式同 1.3.1, 采用蒽酮-硫酸比色法^[29]测定可溶性糖和淀粉含量, 可溶性糖及淀粉含量即为非结构性碳水化合物(non-structural carbohydrates, NSC)含量。并计算花前 NSC 转运量(NSC translocation amount of pre-silking in stem and leaf, NSCRA)、花前 NSC 转运率(NSC translocation rate of pre-silking in stem and leaf, NSCRR, %)、花前 NSC 转运量对 NSC 的贡献率(contribution rate of

NSC translocation amount of pre-silking in stem and leaf, CNSCRA, %)等指标^[30-31], 计算公式如下:

$$\text{NSCRA} = \frac{\text{吐丝后 7 d 茎叶 NSC 积累量} - \text{成熟期茎叶 NSC 积累量}}{\text{成熟期茎叶 NSC 积累量}} \times 100\%$$
 (5)

$$\text{NSCRR} = \frac{\text{花前 NSC 转运量}}{\text{吐丝后 7 d 茎叶 NSC 积累量}} \times 100\%$$
 (6)

$$\text{CNSCRA} = \frac{\text{花前 NSC 转运量}}{\text{成熟期植株 NSC 积累量}} \times 100\%$$
 (7)

1.3.3 氮素积累与转运测定 2023—2024 年, 取样方式同 1.3.1, 采用凯氏定氮法^[32]测定各器官全氮含量。并计算整株的花前氮素转运量(nitrogen translocation amount of pre-silking in stem and leaf, NRA)、花前氮素转运率(nitrogen translocation rate of pre-silking in stem and leaf, NRR, %)、花前氮素转运量对氮素的贡献率(contribution rate of nitrogen translocation amount of pre-silking in stem and leaf, CNRA, %)等指标^[30-31], 计算公式如下:

$$\text{NRA} = \text{吐丝后 7 d 茎叶氮素积累量} - \text{成熟期茎叶氮素积累量}$$
 (8)

$$\text{NRR} = \frac{\text{花前氮素转运量}}{\text{吐丝后 7 d 茎叶氮素积累量}} \times 100\%$$
 (9)

$$\text{CNRA} = \frac{\text{花前氮素转运量}}{\text{成熟期植株氮素积累量}} \times 100\%$$
 (10)

1.3.4 粗蛋白含量的测定 样品于 105℃下烘 30 min 杀青, 80℃下烘干至恒重并进行粉碎, 过 40 目筛, 采用凯氏定氮法测定粗蛋白含量^[32]。

1.3.5 粗蛋白产量计算 粗蛋白产量=叶片粗蛋白含量(%) × 叶片总鲜重(kg hm⁻²) + 茎秆粗蛋白含量(%) × 茎秆总鲜重(kg hm⁻²) + 穗部粗蛋白含量(%) × 穗部总鲜重(kg hm⁻²) (11)

1.3.6 试验区 2023—2024 年降雨量及平均气温

根据甘肃省农业科学院定西试验站气象资料统计(图 1), 试验区 2023 年全年降雨量 369.6 mm, 属

偏早年, 玉米大喇叭口期、抽雄期、吐丝期、灌浆成熟期降雨量分别为 67.7、19.4、18.4 和 24.8 mm, 且 80%以上为 5 mm 以下无效降雨, 玉米干旱胁迫较为严重, 影响玉米生长发育; 2024 年全年降雨量为 426.8 mm, 属平水年, 玉米大喇叭口期、抽雄期、吐丝期、灌浆成熟期降雨量分别为 51.5、27.8、3.3、19.2 mm, 吐丝期玉米遭遇严重干旱, 对青贮玉米生长发育不利, 2023—2024 年全年平均气温分别为 7.8℃、8.2℃, 玉米生育期平均气温均以 7 月下旬到 8 月上旬最高。

1.4 数据统计与分析

采用 Excel 2016 及 SPSS 26.0 软件进行数据的整理汇总、方差分析(ANOVA)、多重比较(Duncan 法), 以 $P < 0.05$ 为显著水平, $P < 0.01$ 为极显著水平。

2 结果与分析

2.1 不同密度下氮肥运筹对饲草玉米干物质积累与转运的影响

氮肥追施可显著降低花前干物质转运量、花前干物质转运率及花前干物质转运对成熟期植株干重产量的贡献率, 并有效提高花后干物质积累量(表 2)。T1、T2 花后干物质积累量分别较 CK1 提高 44.35%~48.23%和 21.30%~23.95%, 均差异显著($P < 0.05$); T3、T4 花后干物质积累量分别较 CK2 提高 1.31%~10.45%和 1.88%~9.91%, 均差异显著($P < 0.05$), T3 和 T4 间无显著差异。2024 年降水量高于 2023 年, 因此同一密度条件下, 花后干物质积累量、转运量及转运率均高于 2023 年。

2.2 不同密度下氮肥运筹对饲草玉米非结构性碳水化合物积累与转运的影响

氮肥追施可显著降低花前 NSC 转运量、花前 NSC 转运率及花前 NSC 转运对成熟期植株 NSC 积累的贡献率, 显著促进花后 NSC 累积(表 3)。与 CK1

表 2 不同处理对饲草玉米干物质积累与转运的影响

Table 2 Effects of different treatments on post-flowering dry matter accumulation and remobilization in forage corn

年份 Year	处理 Treatment	花前干物质转运量 DRA (kg hm ⁻²)	花后干物质积累量 DAA (kg hm ⁻²)	花前干物质转运率 DRR (%)	花前干物质转运量对干 重产量的贡献率 CDRA (%)
2023	CK1	5700.00 a	6708.00 c	35.19 a	23.31 a
	T1	3900.00 b	9683.33 a	27.37 b	5.13 c
	T2	1500.00 c	8136.67 b	11.90 c	16.05 b
	CK2	3187.50 a	8829.33 b	22.08 a	11.33 a
	T3	2387.50 b	9751.67 a	17.93 b	8.87 b
	T4	1875.00 c	9704.00 a	11.76 c	6.98 c

(续表 2)

年份 Year	处理 Treatment	花前干物质转运量 DRA (kg hm ⁻²)	花后干物质积累量 DAA (kg hm ⁻²)	花前干物质转运率 DRR (%)	花前干物质转运量对干 重产量的贡献率 CDRA (%)
2024	CK1	8100.00 a	7207.33 c	42.19 a	30.68 a
	T1	6600.00 b	10,683.33 a	37.29 b	12.98 c
	T2	4050.00 c	8933.33 b	25.23 c	25.29 b
	CK2	6375.00 a	9895.83 b	35.79 a	21.80 a
	T3	5250.00 b	10,025.00 a	30.11 b	19.05 b
	T4	4500.06 c	10,081.67 a	23.30 c	16.55 c

处理同表 1。表中不同字母表示同一密度下各施氮水平间差异显著($P < 0.05$)。
Treatments are the same as those given in Table 1. Different letters indicate significant differences among nitrogen treatments within the same planting density at the 0.05 level. DRA: dry matter translocation amount of pre-silking in stem and leaf; DAA: dry matter accumulation amount of post-silking in stem and leaf; DRR: dry matter translocation rate of pre-silking in stem and leaf; CDRA: contribution rate of dry matter translocation amount of pre-silking in stem and leaf.

表 3 不同处理对饲草玉米非结构性碳水化合物积累与转运的影响
Table 3 Effects of different treatments on post- flowering non-structural carbohydrates accumulation and remobilization in forage maize

年份 Year	处理 Treatment	花前 NSC 转运量 NSCRA (kg hm ⁻²)	花后 NSC 积累量 NSCAA (kg hm ⁻²)	花前 NSC 转运率 NSCRR (%)	花前 NSC 转运量对 NSC 的贡献率 CNSCRA (%)
2023	CK1	3652.60 a	5899.61 c	89.33 a	30.06 a
	T1	2808.47 b	7693.03 a	78.44 b	16.13 c
	T2	2344.29 c	6965.17 b	80.19 b	21.57 b
	CK2	2540.33 a	4721.21 c	89.38 a	27.50 a
	T3	2089.51 b	5676.62 b	78.58 b	20.91 b
	T4	1679.58 c	7930.22 a	69.29 c	15.78 c
2024	CK1	4168.06 a	6259.76 c	88.77 a	35.22 a
	T1	3172.98 b	8053.48 a	75.16 b	20.60 c
	T2	2611.64 c	7325.18 b	77.06 b	25.17 b
	CK2	2796.46 a	5081.12 c	85.57 a	29.65 a
	T3	2260.07 b	6036.67 b	76.54 b	22.43 b
	T4	1832.47 c	8290.40 a	69.62 c	16.24 c

处理同表 1。表中不同字母表示同一密度下各施氮水平间差异显著($P < 0.05$)。NSC: 非结构性碳水化合物。
Treatments are the same as those given in Table 1. Different letters indicate significant differences among nitrogen treatments within the same planting density at the 0.05 level. NSC: non-structural carbohydrates; NSCRA: NSC translocation amount of pre-silking in stem and leaf; NSCAA: NSC accumulation amount of post-silking in stem and leaf; NSCRR: NSC translocation rate of pre-silking in stem and leaf; CNSCRA: contribution rate of NSC translocation amount of pre-silking in stem and leaf.

相比, T1、T2 花前 NSC 转运量分别降低 23.11%~23.87%和 35.82%~37.34%, 花前 NSC 转运率分别降低 10.89%~13.61%和 9.14%~11.71%, 花前 NSC 转运对 NSC 的贡献率分别降低 13.93%~14.62%和 8.49%~10.05%, 但花后 NSC 积累量分别提高 28.65%~30.40%、17.02%~18.06%, 差异均达显著水平($P < 0.05$); 与 CK2 相比, T3、T4 花前 NSC 转运量分别降低 17.75%~19.18%、33.88%~34.47%, 花前 NSC 转运率分别降低 9.03%~10.80%、15.95%~20.09%, 花前 NSC 转运对 NSC 的贡献率分别降低 6.59%~7.22%、11.72%~13.41%, 花后 NSC 积累量分

别提高 18.81%~20.24%、63.16%~67.97%, 差异均达显著水平($P < 0.05$)。不同年份间同一密度条件下, 2024 年度花后 NSC 积累量及转运量均高于 2023 年。

2.3 不同密度下氮肥运筹对青贮玉米氮素积累与转运的影响

氮肥追施可显著提高花前氮素转运量、花前氮素转运率及花后氮素积累量, 降低花前氮素转运对成熟期植株氮素积累的贡献率(表 4)。花前氮素转运量 T1、T2 分别较 CK1 提高 60.45%~68.51%和 37.34%~49.07%; T3、T4 分别较 CK2 提高 8.68%~16.34%、43.52%~51.22%, 差异均达显著水平($P < 0.05$);

表 4 不同处理对青贮玉米氮素积累与转运的影响
Table 4 Effects of different treatments on post- flowering nitrogen accumulation and remobilization in forage maize

年份 Year	处理 Treatment	花前氮素转运量 NRA (kg hm ⁻²)	花后氮素积累量 NAA (kg hm ⁻²)	花前氮素转运率 NRR (%)	花前氮素转运量对氮素的贡献率 CNRA (%)
2023	CK1	119.65 c	173.00 c	53.28 b	36.72 a
	T1	191.98 a	307.28 a	61.72 a	26.60 b
	T2	164.33 b	230.87 b	63.03 a	15.76 c
	CK2	109.16 c	165.14 c	47.46 b	23.66 a
	T3	118.64 b	326.77 a	54.03 a	17.78 b
	T4	156.67 a	257.68 b	53.96 a	12.64 c
2024	CK1	125.77 c	187.00 c	59.66 b	42.28 a
	T1	211.94 a	321.81 a	66.75 a	32.70 b
	T2	187.49 b	245.12 b	64.94 a	18.89 c
	CK2	114.83 c	179.40 c	52.07 b	24.75 a
	T3	133.59 b	272.71 b	63.33 a	18.88 b
	T4	173.65 a	342.25 a	63.07 a	13.81 c

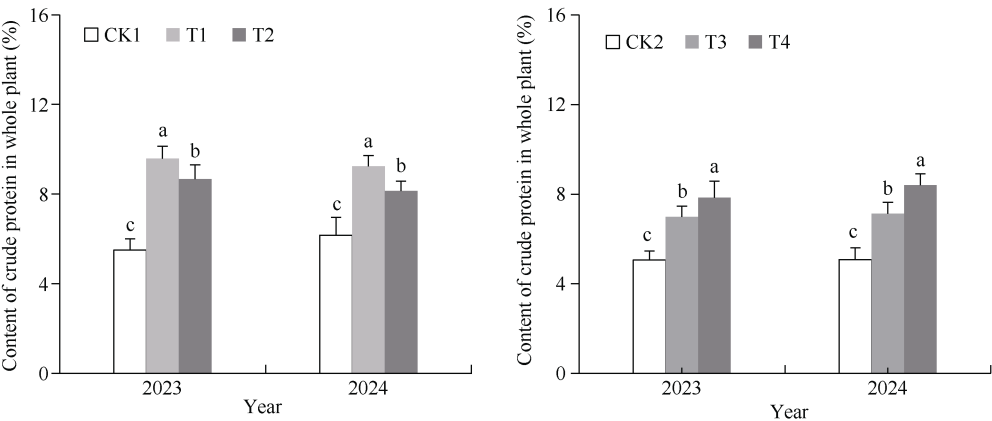
处理同表 1。表中不同字母表示同一密度下各施氮水平间差异显著($P < 0.05$)。
Treatments are the same as those given in Table 1. Different letters indicate significant differences among nitrogen treatments within the same planting density at the 0.05 level. NRA: nitrogen translocation amount of pre-silking in stem and leaf; NAA: nitrogen accumulation amount of post-silking in stem and leaf; NRR: nitrogen translocation rate of pre-silking in stem and leaf; CNRA: contribution rate of nitrogen translocation amount of pre-silking in stem and leaf.

花前氮素转运率 T1、T2 分别较 CK1 提高 7.09%~8.44%、5.28%~9.75%, T3、T4 分别较 CK2 提高 6.57%~11.26%、6.50%~11.00%, 差异均达显著水平 ($P < 0.05$); 花后氮素积累量 T1、T2 分别较 CK1 提高 72.09%~77.62%、31.08%~33.45%, T3、T4 分别较 CK2 提高 52.01%~97.87%、56.04%~90.77%, 差异均达显著水平 ($P < 0.05$)。不同年份间同一密度条件下, 2024 年度花后氮素积累量、转运量及转运率均高于 2023 年。

2.4 不同密度下氮肥运筹对青贮玉米粗蛋白含量和粗蛋白产量的影响

种植密度和施肥作为关键调控因子, 可干预饲

草玉米植株内部的碳氮代谢过程, 直接影响光合产物与氮素吸收利用的平衡, 进而决定作物的最终生物量, 调控粗蛋白的合成效率与积累水平。如图 2 所示, T1、T2 粗蛋白含量及 T1 粗蛋白产量均显著高于 CK1 ($P < 0.05$), 其中, 与 CK1 相比, T1 粗蛋白含量平均提高 62.18%、粗蛋白产量平均提高 17.95%, T2 粗蛋白含量平均提高 44.80%; T3、T4 粗蛋白含量和产量均显著高于 CK2 ($P < 0.05$), 其中, 与 CK2 相比, T3 粗蛋白含量平均提高 39.25%、粗蛋白产量平均提高 35.37%, T4 粗蛋白含量平均提高 60.15%、粗蛋白产量平均提高 55.83%, 且同一施肥条件下随青贮玉米密度增大, 粗蛋白含量降低。



(图 2)

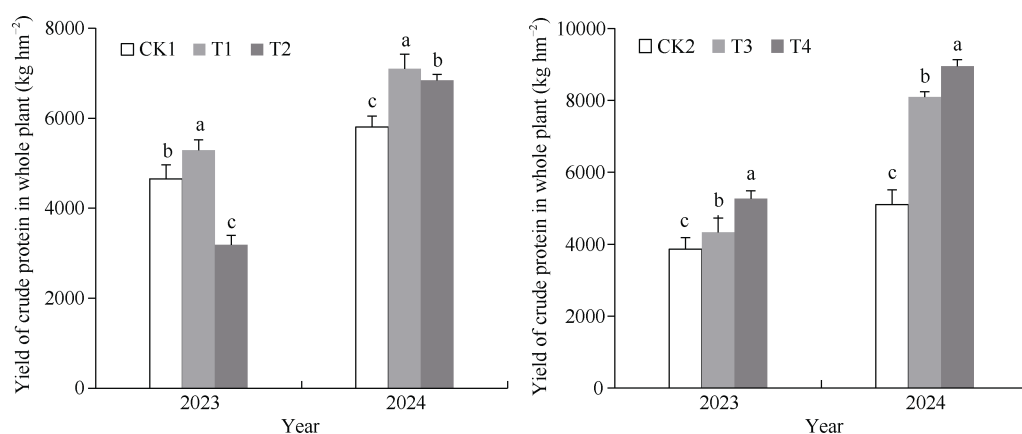


图 2 2023–2024 年同一密度条件下不同施肥处理的青贮玉米粗蛋白含量和粗蛋白产量

Fig. 2 Crude protein content and crude protein yield in whole plant under different fertilization treatments at the same planting density during 2023–2024

处理同表 1。图中不同字母表示同一年份处理间差异显著 ($P < 0.05$)。

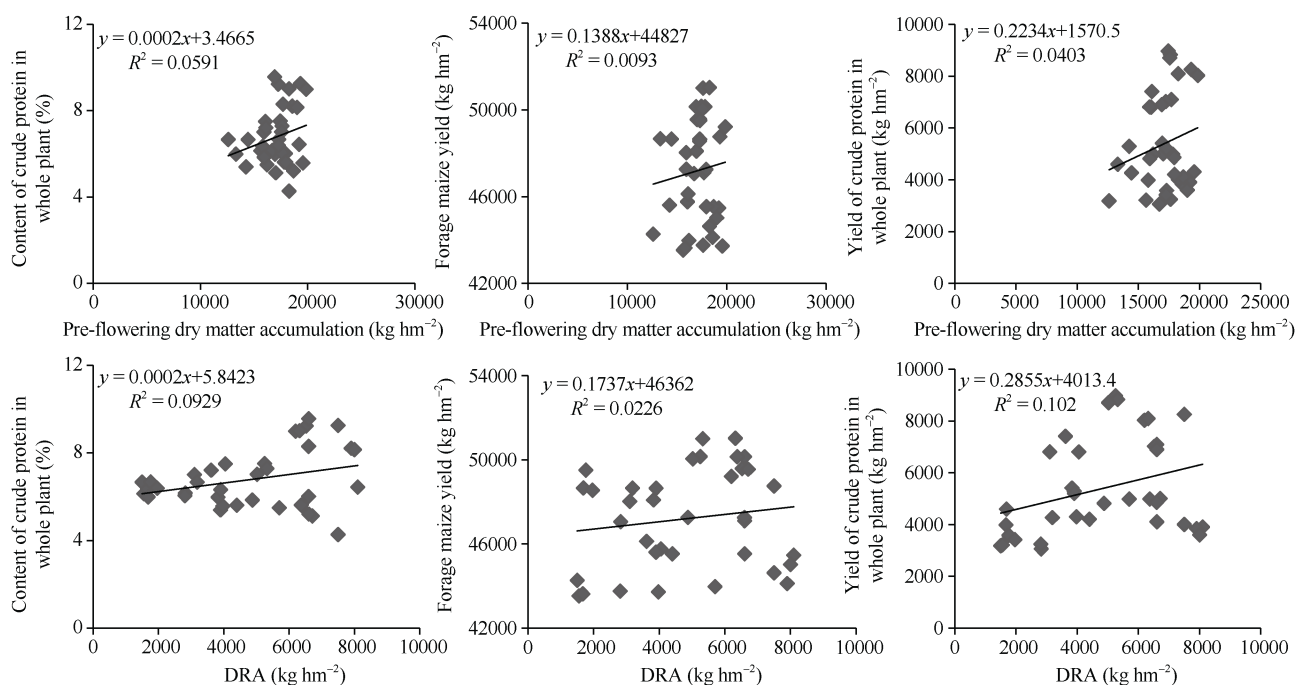
Treatments are the same as those given in Table 1. Different letters indicate significant differences among treatments within the same year at the 0.05 level.

2.5 植株碳代谢与青贮玉米粗蛋白含量和粗蛋白产量的相关性

干物质和非结构性碳水化合物(NSC)是植株碳代谢的重要指标,与作物产量和品质密切相关。本试验条件下,花前干物质积累量、花前干物质转运量与粗蛋白含量,青贮玉米产量与粗蛋白产量均无显著相关性;花后干物质积累量与粗蛋白含量无显著相关性,但与青贮玉米产量($R^2 = 0.1547^*$)及粗蛋白产量($R^2 = 0.1723^*$)呈显著正相

关(图 3)。

花前 NSC 积累量与粗蛋白含量($R^2 = 0.1896^{**}$)呈极显著负相关,与青贮玉米产量($R^2 = 0.1523^*$)及粗蛋白产量($R^2 = 0.1566^*$)呈显著负相关;花前 NSC 转运量与粗蛋白含量无显著相关性,与青贮玉米产量($R^2 = 0.1789^{**}$)及粗蛋白产量($R^2 = 0.1758^{**}$)呈极显著负相关;花后 NSC 积累量与青贮玉米产量及粗蛋白产量均无显著相关性,而与粗蛋白含量($R^2 = 0.2155^{**}$)呈极显著正相关(图 4)。



(图 3)

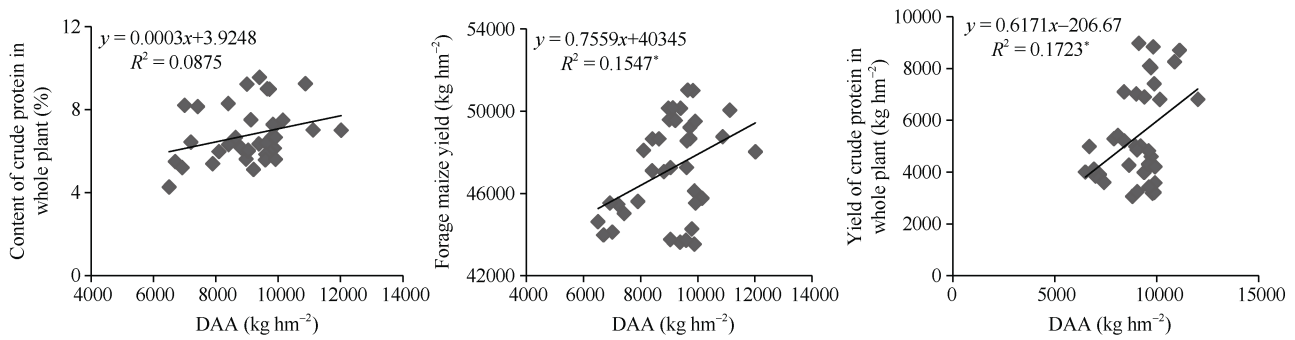


图3 花前干物质积累量、花前干物质转运量(DRA)及花后干物质积累量(DAA)与粗蛋白含量、青贮玉米产量及粗蛋白产量的相关性
Fig. 3 Correlations of pre-flowering dry matter accumulation, pre-flowering dry matter translocation, and post-flowering dry matter accumulation with crude protein content, forage maize yield, and crude protein yield under different nitrogen application rates
 缩写同表2。*表示在0.05水平相关性显著($n=36$)。

Abbreviations are the same as those given in Table 2. * represents significant correlation at $P < 0.05$ ($n = 36$).

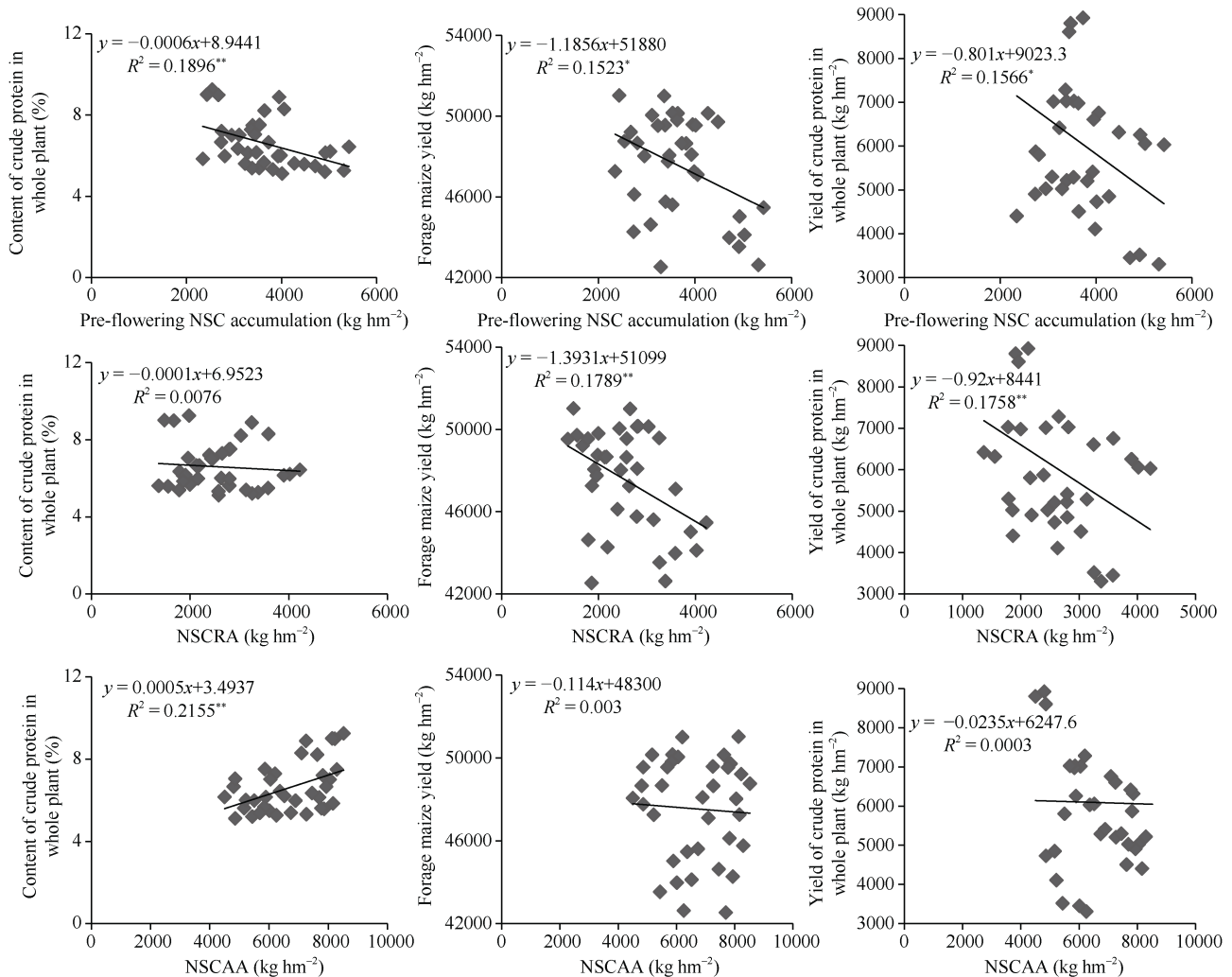


图4 花前NSC积累量、花前NSC转运量(NSCRA)及花后NSC积累量(NSCAA)与粗蛋白含量、青贮玉米产量及粗蛋白产量的相关性
Fig. 4 Correlations of pre-flowering NSC accumulation, pre-flowering NSC translocation, and post-flowering NSC accumulation with crude protein content, forage maize yield, and crude protein yield under different nitrogen application rates

缩写同表3。*和**分别表示在0.05和0.01水平相关性显著($n=36$)。NSC: 非结构性碳水化合物。

Abbreviations are the same as those given in Table 3. * and ** represent significant correlation at $P < 0.05$ and $P < 0.01$ levels, respectively ($n = 36$). NSC translocation amount of pre-silking in stem and leaf.

2.6 植株氮代谢与青贮玉米粗蛋白含量和粗蛋白产量的相关性

花前氮素积累量、花前氮素转运量及花后氮素积累量可反映植株氮代谢特征。如图 5 所示, 花前氮素积累量与粗蛋白含量、青贮玉米产量及粗蛋白产量均

无显著相关性; 花前氮素转运量与鲜草产量无显著相关性, 但与粗蛋白含量($R^2 = 0.1263^*$)呈显著正相关; 花后氮素积累量与粗蛋白含量($R^2 = 0.1764^{**}$)呈极显著正相关, 而与青贮玉米产量($R^2 = 0.1582^*$)及粗蛋白产量($R^2 = 0.1682^*$)呈显著正相关(图 5)。

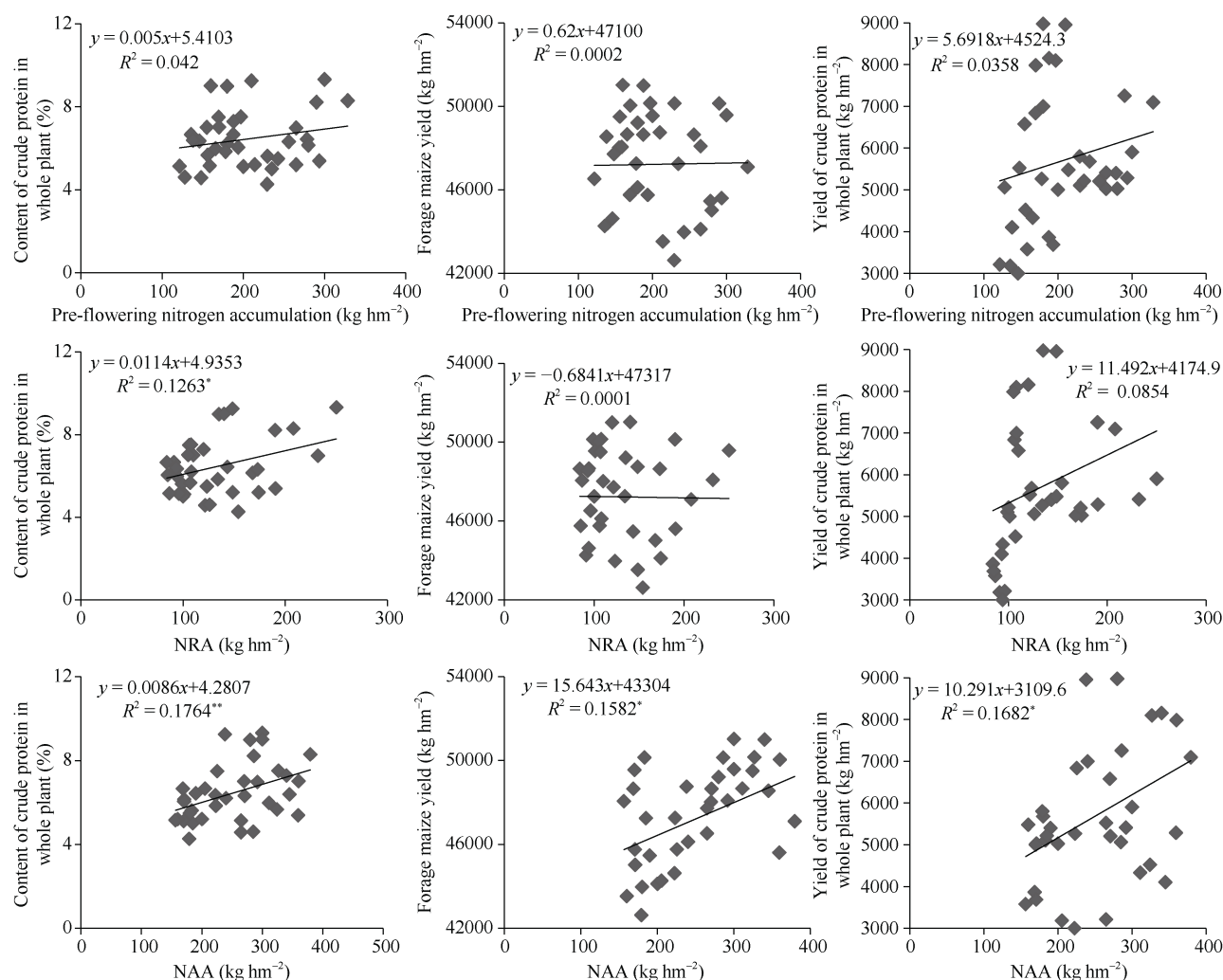


图 5 花前氮素积累量、花前氮素转运量(NRA)及花后氮素积累量(NAA)与粗蛋白含量、青贮玉米产量及粗蛋白产量的相关性

Fig. 5 Correlations of pre-flowering nitrogen accumulation, pre-flowering nitrogen translocation, and post-flowering nitrogen accumulation with crude protein content, forage maize yield, and crude protein yield under different nitrogen application rates

缩写同表 4。*和**分别表示在 0.05 和 0.01 水平相关性显著($n = 36$)。

Abbreviations are the same as those given in Table 4. * and ** represent significant correlation at $P < 0.05$ and $P < 0.01$ levels, respectively ($n = 36$).

3 讨论

3.1 合理的密度和氮肥运筹显著促进青贮玉米花后碳氮代谢

密度和施肥通过调节氮素吸收、转运和同化等过程, 显著调控饲草玉米碳氮代谢, 进而影响玉米的生长和品质。合理的种植密度通过增加单位面积内的穗数, 优化玉米植株间的竞争关系, 提高光合

作用效率, 促进 NSC 的积累^[33-35], 最大化干物质的合成与积累^[36]。但也有研究显示, 密度过高会导致植株间光资源竞争加剧, 抑制植株正常发育, 进而降低 NSC 的积累和转运效率^[37], 导致单株干物质积累减少, 光合速率下降, 最终影响整体产量^[38]。适宜的种植密度能够优化玉米群体结构, 提高光能利用效率, 从而促进氮素的吸收和代谢, 提高玉米籽粒产量^[39]。在合理的密度下, 玉米叶片的光合作用增

强, 有助于提高硝酸还原酶(NR)和谷氨酸脱氢酶(GDH)的活性, 这些酶是氮代谢中的关键酶, 直接参与氮素的同化和再分配^[40]。相反, 过高的种植密度会导致个体间竞争加剧, 氮素吸收不足, 从而降低氮代谢效率^[41]。本试验条件下, 6.0 万株 hm^{-2} 密度下花前氮素转运量、花前氮素转运率及花前氮素转运对氮素的贡献率均高于 7.5 万株 hm^{-2} (表 4), 这可能是因为密度较低时, 单株的光合作用和养分吸收能力更强, 从而提高了氮素的转运效率; 这与已有报道一致^[42-43]; 同样, 花前 NSC 转运量和花后 NSC 积累量均表现为密度 6.0 万株 hm^{-2} 高于 7.5 万株 hm^{-2} (表 4), 与已有报道一致^[44-45], 6.0 万株 hm^{-2} 时的花前干物质转运量、花前干物质转运率及花前干物质转运对干重产量的贡献率均高于 7.5 万株 hm^{-2} , 但花后干物质积累量低于 7.5 万株 hm^{-2} (表 2)。且 2024 年相关数据高于 2023 年, 这可能是因为 2024 年降水量整体高于 2023 年。因此, 增密可限制花前氮素向花后转移, 提高花后氮素积累量, 促进花前干物质向花后转移, 提高花后干物质积累量, 但对 NSC 转运和积累有一定的限制, 而促进花后氮素积累、花后干物质和 NSC 积累的最佳密度有待进一步研究。

氮肥的合理分期施用能够显著提高玉米营养器官的 NSC 含量, 同时提高干物质向籽粒的转运效率。小喇叭口期追施氮肥可显著提高茎秆中 NSC 含量, 从而增加玉米产量^[46-47]。同时, 氮磷钾肥的不同处理也会影响饲草玉米各阶段 NSC 的含量, 进而影响玉米产量和饲料品质^[48]。分次施用氮肥且施氮量为 181 kg hm^{-2} 的处理, 其干物质积累和转运效率均达到最优, 籽粒产量也显著提高^[49]。在玉米成熟期, 追施氮肥能够显著增加花前营养器官同化物的转运量及其对籽粒的贡献率, 可见氮肥的分期施用不仅优化了营养器官的 NSC 和干物质积累, 还促进了干物质的有效转运^[50]。因此, 科学合理的施肥策略和种植密度管理可最大化干物质、NSC 积累与向籽粒/茎秆的转运效率, 提高青贮玉米干物质、NSC 的积累量和转运量, 实现高产优质。本试验条件下, 随着氮肥追施比例的增加, 花前干物质转运量、花前干物质转运率及花前干物质转运对干重产量的贡献率均逐渐降低, 但花后干物质积累量逐渐提高(表 2); 花前 NSC 的转运量、花前 NSC 转运对 NSC 的贡献率均逐渐降低, 但花后 NSC 积累量逐渐提高, 且同一密度条件下 2024 年相关指标高于 2023 年(表 3),

这可能与其年降水量关系密切, 该试验结果与已有结果相同^[39-40]。因此, 氮肥追施可降低饲草玉米花前干物质、NSC 的转运量, 提高花后干物质、NSC 积累量, 但花前干物质转运对干重产量的贡献率及花前 NSC 转运对 NSC 的贡献率有一定限制, 同时促进花后干物质、NSC 积累量的最佳氮肥追施量有待进一步研究。

科学合理的种植密度和施肥能够显著提高饲草玉米叶片叶绿素含量进而提高光合作用效率, 为氮代谢提供充足的能量和碳骨架, 从而增强 NR 和 GDH 的活性, 促进氮素的有效吸收和利用, 优化饲草玉米的氮代谢特征, 促进氮素吸收、调控酶活性以及提高蛋白质代谢效率, 最终提升饲草玉米的产量和品质^[51-52]。其中, 追肥促进饲草玉米营养品质的效果较好, 但应当注意追肥施用的最佳时间^[53]。本试验条件下, 随着氮肥追施, 花前氮素转运量逐步增加, 花前氮素转运对氮素的贡献率逐渐降低, 在相同密度条件下, 大喇叭口期追施 40%氮肥时花后氮素积累量达到最高(表 4), 这可能是由于追肥满足了作物在生殖生长阶段对氮素的高需求, 从而提高了花后氮素积累量; 且 2024 年相关指标高于 2023 年, 这可能与年降水量密切相关, 与已有报道相同^[43,54-55]。因此, 氮肥追施在一定程度上限制花前氮素转运对氮素的贡献率, 提高花后氮素积累量, 同时促进花后氮素积累量的最佳氮肥追施量有待进一步研究。

3.2 密度和施肥通过调节碳氮代谢影响粗蛋白合成

大田食用玉米以籽粒生产为首要目标, 注重籽粒产量和品质, 而饲草玉米以地上部分为收获物, 其品质是关注的重点。虽然食用玉米与青贮玉米生长规律基本相同, 但调控目标有差异, 本试验以青贮玉米品质调控为出发点, 研究不同密度下氮肥运筹对青贮玉米碳氮积累与转运特征的影响, 可为该区青贮玉米高效优质生产和畜牧业健康持续发展提供理论依据和技术支撑。种植密度和施肥管理通过协同调控碳、氮代谢与转运效率, 显著影响饲草玉米产量及粗蛋白含量。研究显示, 适度密植可优化群体光分布, 提高光合碳同化能力, 促进 NSC 的合成并转运至籽粒, 为粗蛋白合成提供碳骨架^[56-57]。密植条件下, 通过糖-氨基酸代谢耦合作用, 玉米茎秆中 NSC 积累量增加 15%~20%, 显著提升籽粒中粗蛋白含量^[58]。但也有研究表明, 过高密度会导致

植株间光竞争加剧,降低叶片光合速率和碳转运效率,同时抑制氮素吸收,使粗蛋白含量下降^[59-60]。分阶段施氮可通过提高饲草玉米叶片和茎秆硝酸还原酶活性和籽粒谷丙转氨酶活性从而显著促进粗蛋白合成^[13]。密度与施肥的交互效应对碳氮平衡具有关键作用。低密度下增施氮肥易导致碳代谢冗余,大量 NSC 滞留于茎秆而未被用于蛋白合成^[58];而高密度配合控释氮肥可实现碳氮比(C/N)的优化,使籽粒粗蛋白含量最大化^[61]。氮素积累量是饲草玉米粗蛋白含量的物质基础,而氮素转运量直接决定饲草玉米粗蛋白的最终分布。因此,充足的氮素供应促进叶片扩展和光合作用^[62],为氨基酸和蛋白质合成提供必需原料,且茎叶中的氮素积累量与粗蛋白含量呈显著正相关^[63]。另外,氮素转运量通过调控生育后期氮素的再分配效率^[64],进一步优化粗蛋白的空间分布^[65],且分期追施氮肥可同步提升花前氮素积累量和转运率,使粗蛋白含量显著提高^[13,66-67]。本试验条件下,T1 和 T4 通过显著提高花后干物质和 NSC 积累量(表 2 和表 3)、花前氮素转运量、转运率和花后氮素积累量(表 4)而优化了饲草玉米碳氮代谢,同时,在粗蛋白含量与花前氮素转运量($R^2 = 0.1263^*$)、花后氮素积累量($R^2 = 0.1764^{**}$)、花后 NSC 积累量($R^2 = 0.2155^*$)呈显著或极显著正相关的前提下促进粗蛋白合成,使粗蛋白含量显著提高 39.25%~62.18%,粗蛋白产量显著提高 17.95%~55.83% (图 2),与已有结果一致^[50,68]。

4 结论

密度和氮肥追施通过调控半干旱区青贮玉米碳氮积累动态与转运效率,促进植株碳氮代谢协同,进而保障饲草玉米养分平衡供给,显著提高粗蛋白含量。大喇叭口期追施不同量的氮肥,通过显著提高花后干物质和 NSC 积累量、花前氮素转运量、转运率和花后氮素积累量,从而提升青贮玉米粗蛋白含量。本试验区 6.0 万株 hm^{-2} 密度下大喇叭口期追施 40%氮肥(T1)和 7.5 万株 hm^{-2} 密度下大喇叭口期追施 60%氮肥(T4)青贮玉米粗蛋白含量分别达 9.42% 和 8.12%,是提升该区饲草玉米品质的有效措施。为推动该区青贮玉米生产潜力的深度挖掘,未来的栽培策略需向精准化与智能化转型,关键在于破解种植密度与氮肥效益的耦合关系,在适度提高种植密度以最大化光能利用效率的同时,通过优化氮肥施用精准匹配高密度群体的营养需求,实现源库协

调。此外,应积极探索新型智能肥料及肥料增效剂的集成应用模式,通过多元化的技术赋能,为青贮玉米产量与品质的协同突破提供核心驱动力。

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