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种植翻压光叶紫花苕配合氮肥减施提高烤烟产量和土壤质量

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摘要:探讨云南烟区绿肥翻压量配合氮肥减施的效应, 以期为烤烟生产的节肥增效提供理论依据和技术途径。基于2017年开始的田间试验, 于2022年研究了翻压不同量光叶紫花苕配合减氮15%及30%对烤烟产量和土壤质量的影响。相比冬闲一烤烟常规施肥(F_{100}), 22500~30000 kg·hm⁻²光叶紫花苕翻压量配合减施常规量氮肥15%和30%, 烤烟产量提升了4.85%~9.94% ($P<0.05$)。翻压光叶紫花苕配合减施氮肥改善了土壤养分性状, 其中, 光叶紫花苕翻压30000 kg·hm⁻²配合减氮30%处理土壤有机质和可溶性有机氮含量最高, 相比 F_{100} 处理分别提高了28.2%和242.6% ($P<0.05$)。光叶紫花苕翻压22500和30000 kg·hm⁻²配合减氮30%处理土壤质量指数相比 F_{100} 分别提高了49.1%和72.9% ($P<0.05$)。不同施氮水平下, 土壤碳、氮、磷相关水解酶活性随着绿肥翻压量的增加而增加。偏最小二乘路径分析(PLS-PM)和随机森林分析表明, 烤烟产量主要受土壤有机质及酶活性的影响。因此, 种植翻压绿肥后合理减施氮肥能够提高烤烟产量和土壤质量, 其中翻压光叶紫花苕22500~30000 kg·hm⁻²减施氮肥30%效果突出。

关键词:烤烟; 绿肥; 氮肥减施; 产量; 土壤质量; 土壤酶活性

Planting and incorporation of smooth vetch together with reduced nitrogen fertilizer application enhances tobacco yield and soil quality

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Abstract: The overall aim of our research was to provide a theoretical basis and technical approach to reduce fertilizer use and improve fertilizer use efficiency during tobacco production in Yunnan. To this end, we conducted an experiment in which different amounts of smooth vetch (*Vicia villosa*) were incorporated together with reduced application rates of nitrogen fertilizer to tobacco (*Nicotiana tabacum*), and the yield and soil quality were evaluated. The field experiment commenced in 2017, and the impacts of planting and incorporating varying amounts of smooth vetch together with 30% and 15% reductions in the nitrogen fertilizer application rate on tobacco yield and soil quality were evaluated in 2022. Compared with the conventional fertilization practice of fallow-tobacco (control-F₁₀₀), incorporating 22500 to 30000 kg·ha⁻¹ green manure with a 15% and 30% reduction in the nitrogen fertilizer application rate significantly increased tobacco yield by 4.85%–9.94% ($P<0.05$). The incorporation of smooth vetch with reduced nitrogen fertilizer application also improved soil nutrient properties. Specifically, the treatment with 30000 kg·ha⁻¹ green manure incorporation and a 30% reduction in the nitrogen fertilizer rate resulted in the highest soil organic matter and soluble organic nitrogen contents, which were increased by 28.2% and 242.6%, respectively, compared with those in the control ($P<0.05$). Incorporation of smooth vetch at rates of 22500 and 30000 kg·ha⁻¹, in conjunction with a 30% reduction in the nitrogen application rate, increased the soil quality index by 49.1% and 72.9%, respectively, compared with that in the control ($P<0.05$). Under different nitrogen application levels, the activities of hydrolytic enzymes associated with soil carbon, nitrogen, and phosphorus increased with increasing amounts of incorporated green manure. Partial least squares path modeling and random forest analyses indicated that tobacco yield was primarily influenced by the soil organic matter content and enzyme activity. Therefore, planting and incorporating green manure with the linked reduction of nitrogen fertilizer enhanced both tobacco yield and soil quality, with outstanding effects observed at 22500 to 30000 kg·ha⁻¹ of smooth vetch incorporation with a 30% reduction in nitrogen fertilizer.

Key words: tobacco; green manure; nitrogen fertilizer reduction; yield; soil quality; soil enzyme activity

烤烟(*Nicotiana tabacum*)是我国重要的经济作物,其产量和品质直接关系到植烟地区农民的收入^[1]。烤烟的种植主要集中在云南、贵州和四川等地区,这些地区具有得天独厚的自然条件,适合烤烟生长^[2]。烤烟对氮素极其敏感,传统的烤烟种植模式往往过度依赖于高量的氮肥施用来追求高产^[3]。然而,长期过量施用氮肥,不仅导致贵州等地烟区土壤结构破坏、烤烟品质下降,还加剧了病虫害的发生和环境污染^[4]。目前,不合理的施肥方式和连作障碍已成为烤烟产量提升的主要限制因素^[5–6]。绿肥是我国传统农业的瑰宝,在提升地力、减施化肥中作用巨大^[7–8]。绿肥—经济作物轮作已成为支撑作物可持续生产的关键农业实践,对作物产量和土壤多功能性等产生积极影响^[9]。绿肥—烤烟轮作是减轻过量化肥施用带来不利影响和破解植烟连作障碍的有效路径^[10]。前人研究表明绿肥—烟草轮作可明显提升土壤肥力、增加烤烟产量^[11]、改善烤烟品质^[12]。

光叶紫花苕(*Vicia villosa*)是云南烟区烟草轮作制度中常见的豆科绿肥作物,具有生物固氮能力强、生长期短和适应性广等特点^[13]。种植利用光叶紫花苕等绿肥能够改善土壤质量和提高烤烟产量^[14]。研究人员对比多种供试绿肥效果,发现种植利用光叶紫花苕烟叶农艺性状明显改善,其经济效益最优^[12]。同时,种植利用光叶紫花苕配施减量氮肥能够使烟田节肥、增效^[15],然而,绿肥翻压量的适宜范围因地区、作物、土壤条件和氮肥投入量等因素的不同而异^[16]。因此,在烤烟生产中,氮肥减施下确定适宜的绿肥翻压量对实现绿肥的最大效益至关重要。以往关于绿肥—烤烟轮作的研究多关注烤烟的产量和品质,鲜少关注土壤质量和酶活性,开展有关研究可为烟田土壤长期可持续利用提供科学依据。本研究基于5年定位试验(2017–2022年),以氮肥减施为背景,研究绿肥光叶紫花苕不同翻压量对烤烟产量和土壤质量的影响,综合评价云南烟区种植利用光叶紫花苕的氮肥减施效应,为我国云南烟区的烤烟高产与节肥增效提供理论依据和实践指导。

1 材料与方法

1.1 试验地概况

试验点位于云南省昆明市云南省农业科学院基地,属亚热带高原季风气候,该地区年平均气温 14.2 °C,降水量 987.1 mm。试验地土壤为红色石灰土,其基础理化性状见表 1。

表 1 土壤基础理化性状

Table 1 Soil basic physical and chemical properties

pH	有机质 Soil organic matter (g·kg ⁻¹)	全氮 Total nitrogen (g·kg ⁻¹)	碱解氮 Alkaline hydrolysable nitrogen (mg·kg ⁻¹)	有效磷 Available phosphorus (mg·kg ⁻¹)	速效钾 Available potassium (mg·kg ⁻¹)
7.10	22.1	0.90	76.1	145.0	30.7

1.2 试验材料

供试绿肥和烤烟来自当地主栽品种,分别是光叶紫花苕和 K326。光叶紫花苕的 N、P、K 含量分别为 33.8 g·kg⁻¹、2.5 g·kg⁻¹和 22.4 g·kg⁻¹。

1.3 试验设计

该田间试验于 2017 年 10 月种植绿肥(光叶紫花苕),共设 10 个处理,分别为冬闲不施氮肥(CK)、冬闲+常规施用氮肥(F₁₀₀)、70% 氮肥+绿肥 7500 kg·hm⁻²(F₇₀G_{0.5})、70% 氮肥+绿肥 15000 kg·hm⁻²(F₇₀G_{1.0})、70% 氮肥+绿肥 22500 kg·hm⁻²(F₇₀G_{1.5})、70% 氮肥+绿肥 30000 kg·hm⁻²(F₇₀G_{2.0})、85% 氮肥+绿肥 7500 kg·hm⁻²(F₈₅G_{0.5})、85% 氮肥+绿肥 15000 kg·hm⁻²(F₈₅G_{1.0})、85% 氮肥+绿肥 22500 kg·hm⁻²(F₈₅G_{1.5})和 85% 氮肥+绿肥 30000 kg·hm⁻²(F₈₅G_{2.0})。其中常规氮肥用量为 120 kg·hm⁻²,F₇₀和 F₈₅分别为常规氮肥的 70% 和 85%,磷钾肥施肥量分别为 90 kg·hm⁻²(P₂O₅)和 405 kg·hm⁻²(K₂O)。烟草移植前 20 d 原位翻压绿肥,用量不足的异地移入。小区面积 21 m²,每个处理 3 次重复,随机区组排列,田间管理方式遵循当地种植习惯。

1.4 样品采集与测定

于 2022 年烟草成熟后,烘烤测产。采集各小区土壤样品(5 点法),过 2 mm 筛,其中,一部分鲜土用于土壤可溶性有机物、无机氮(铵态氮 NH₄⁺-N 和硝态氮 NO₃⁻-N)和碳氮磷转化酶活性的测定,其余部分风干,用于分析土壤速效养分,部分干土磨细过 0.15 mm 筛后测定土壤全氮和有机质。土壤基础化学性状测试方法参考《土壤农化分析》^[17],具体如下:土壤有机质(soil organic matter, SOM)采用重铬酸钾外加热法测定;土壤 pH 值采用电位法测定(水土比 1.0:2.5);土壤全氮(total nitrogen, TN)采用 H₂SO₄—催化剂消解,凯氏定氮法测定;采用 KCl 溶液提取土壤无机氮,连续流动分析仪(AA3, SEAL Analytical, 德国)测定浓度;土壤有效磷(available phosphorus, AP)采用 NaHCO₃ 溶液提取,紫外分光光度计(UV-2100, Rayleigh, 中国)测定;土壤速效钾(available potassium, AK)采用 NH₄Ac 浸提,火焰光度法分析;可溶性有机物(dissolved organic matter, DOM)为可溶性有机碳(dissolved organic carbon, DOC)和可溶性有机氮(dissolved organic nitrogen, DON)的总和,采用超纯水浸提,总有机碳分析仪(Multi N/C 2100, Analytik Jena, 德国)测定。

土壤酶活性分为 3 大类,分别参与土壤碳、氮、磷转化,其中与碳转化相关酶类包括 β-葡萄糖苷酶(β-glucosidase, BG)、β-纤维二糖苷酶(β-cellobiosidase, CB)、β-木糖苷酶(β-xylosidase, XYL)和 α-葡萄糖苷酶(α-glucosidases, AG),氮转化酶包括乙酰氨基葡萄糖苷酶(acetylglucosaminidase, NAG)和亮氨酸氨基肽酶(leucine aminopeptidase, LAP),磷转化酶类为碱性磷酸酶(alkaline phosphatase, AKP),均采用荧光微型板酶检测技术分析测定^[18]。

1.5 数据分析

用土壤质量指数(soil quality index, SQI)来衡量土壤健康状况,土壤质量面积指数越大表明土壤健康状况越

好^[19],具体计算公式如下:

$$SL_i = X/X_{\max} \quad (1)$$

$$SQI = 0.5 \times \sum_{i=1}^n SL_i^2 \times \sin\left(\frac{2\pi}{n}\right) \quad (2)$$

式中: SL_i 代表第*i*个土壤指标的线性得分; X 和 $X_{\max}$ 分别代表第*i*个指标的测定值和最大值; n 为土壤指标的总数^[18]。

1.6 统计分析

使用SPSS 22.0进行统计分析,采用单因素方差分析(ANOVA)进行LSD ($P < 0.05$)的多重比较,冗余分析使用Canoco 5.1,随机森林和偏最小二乘路径分析(partial least squares path modeling, PLS-PM)分别使用R语言(R 4.3.2)中的“randomForest”和“plsrm”包,使用Origin 2024绘图。

2 结果与分析

2.1 烤烟产量

如图1所示,与不施肥处理相比,常规施肥和种植翻压绿肥配合减施常规量氮肥15%和30%条件下,烤烟产量均显著提高($P < 0.05$)。相比常规施肥 F_{100} 处理,除了 $F_{70}G_{0.5}$ 处理,不同绿肥翻压量配合减施常规量氮肥30%条件下,烤烟产量均显著增加($P < 0.05$),且随着绿肥翻压量的增加,产量逐渐提升,绿肥翻压15000、22500和30000 $\text{kg} \cdot \text{hm}^{-2}$ 处理烤烟产量分别提高了4.74%、4.85%和5.46%;减施常规量氮肥15%条件下,绿肥翻压15000、22500和30000 $\text{kg} \cdot \text{hm}^{-2}$ 处理烤烟产量分别为2079、2137和2062 $\text{kg} \cdot \text{hm}^{-2}$,相比 F_{100} ,显著增加了6.96%、9.94%和6.11% ($P < 0.05$)。

2.2 土壤养分性状

与 F_{100} 处理相比,减施氮肥15%和30%条件下,绿肥翻压15000~30000 $\text{kg} \cdot \text{hm}^{-2}$ 时,土壤pH值分别显著降低0.23~0.31和0.25~0.27。减施氮肥30%条件下,绿肥翻压30000 $\text{kg} \cdot \text{hm}^{-2}$ 土壤有机质含量相比 F_{100} 处理显著提高28.2%,减施氮肥15%条件下,不同绿肥翻压量处理土壤有机质含量增加了4.0~6.9 $\text{g} \cdot \text{kg}^{-1}$,增幅15.7%~27.1%,其中, $F_{85}G_{2.0} > F_{85}G_{1.5} > F_{85}G_{1.0} > F_{85}G_{0.5}$ (表2)。全氮、有效磷(除了 $F_{85}G_{2.0}$)含量在各处理间无显著差异。相比 F_{100} , $F_{70}G_{1.5}$ 、 $F_{70}G_{2.0}$ 和 $F_{85}G_{2.0}$ 处理土壤速效钾含量分别显著增加了51.7%、60.2%和64.6%。不同绿肥翻压量处理土壤可溶性有机碳、可溶性有机氮(除了 $F_{85}G_{0.5}$)相比 F_{100} 处理分别显著提升了27.2%~44.4%和145%~243%。铵态氮含量以绿肥还田配合减施常规量30%氮肥处理下较高,其中相比 F_{100} , $F_{70}G_{1.0}$ 、 $F_{70}G_{1.5}$ 和 $F_{70}G_{2.0}$ 显著提高了89.3%~195.0%。相比 F_{100} , $F_{70}G_{0.5}$ 、 $F_{70}G_{1.0}$ 、 $F_{85}G_{1.0}$ 、 $F_{85}G_{1.5}$ 和 $F_{85}G_{2.0}$ 处理土壤硝态氮含量显著提高了83.6%~278.2%。

土壤质量指数以CK最低,其次是 F_{100} 处理。不同氮肥减施条件下,土壤质量指数均随着绿肥翻压量增加而

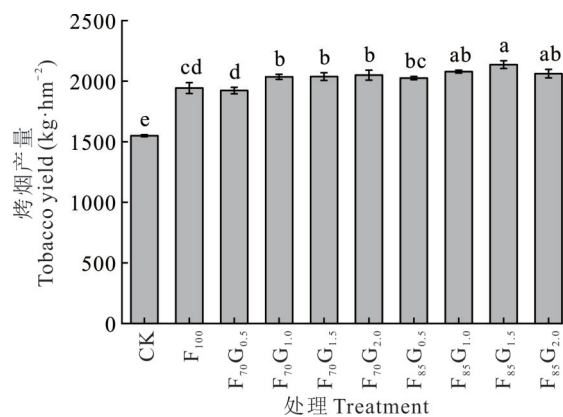


图1 不同施肥处理烤烟产量

Fig. 1 Tobacco yield in different treatments

CK: 冬闲不施氮肥; F_{100} : 冬闲+常规施用氮肥; $F_{70}G_{0.5}$: 70% 氮肥+绿肥 7500 $\text{kg} \cdot \text{hm}^{-2}$; $F_{70}G_{1.0}$: 70% 氮肥+绿肥 15000 $\text{kg} \cdot \text{hm}^{-2}$; $F_{70}G_{1.5}$: 70% 氮肥+绿肥 22500 $\text{kg} \cdot \text{hm}^{-2}$; $F_{70}G_{2.0}$: 70% 氮肥+绿肥 30000 $\text{kg} \cdot \text{hm}^{-2}$; $F_{85}G_{0.5}$: 85% 氮肥+绿肥 7500 $\text{kg} \cdot \text{hm}^{-2}$; $F_{85}G_{1.0}$: 85% 氮肥+绿肥 15000 $\text{kg} \cdot \text{hm}^{-2}$; $F_{85}G_{1.5}$: 85% 氮肥+绿肥 22500 $\text{kg} \cdot \text{hm}^{-2}$; $F_{85}G_{2.0}$: 85% 氮肥+绿肥 30000 $\text{kg} \cdot \text{hm}^{-2}$ 。不同小写字母表示不同处理间存在显著差异 ($P < 0.05$)。下同。CK: No nitrogen fertilizer in winter fallow; F_{100} : Winter fallow with conventional application of nitrogen fertilizer; $F_{70}G_{0.5}$: 70% nitrogen fertilizer with green manure 7500 $\text{kg} \cdot \text{ha}^{-1}$; $F_{70}G_{1.0}$: 70% nitrogen fertilizer with green manure 15000 $\text{kg} \cdot \text{ha}^{-1}$; $F_{70}G_{1.5}$: 70% nitrogen fertilizer with green manure 22500 $\text{kg} \cdot \text{ha}^{-1}$; $F_{70}G_{2.0}$: 70% nitrogen fertilizer with green manure 30000 $\text{kg} \cdot \text{ha}^{-1}$; $F_{85}G_{0.5}$: 85% nitrogen fertilizer with green manure 7500 $\text{kg} \cdot \text{ha}^{-1}$; $F_{85}G_{1.0}$: 85% nitrogen fertilizer with green manure 15000 $\text{kg} \cdot \text{ha}^{-1}$; $F_{85}G_{1.5}$: 85% nitrogen fertilizer with green manure 22500 $\text{kg} \cdot \text{ha}^{-1}$; $F_{85}G_{2.0}$: 85% nitrogen fertilizer with green manure 30000 $\text{kg} \cdot \text{ha}^{-1}$. Different lowercase letters indicated significant differences among different treatments ($P < 0.05$). The same below.

递增。相比 F_{100} , 4个绿肥翻压量配合减施氮肥 30% 处理土壤质量指数分别显著增加 35.9%、37.4%、49.1% 和 72.9%, 减施氮肥 15% 条件下, 绿肥翻压 15000、22500 和 30000 $\text{kg}\cdot\text{hm}^{-2}$ 处理土壤质量指数分别显著提高 37.7%、46.7% 和 71.3% (图 2)。

表 2 不同施肥处理下土壤养分性状

Table 2 Soil nutrients in different treatments

处理 Treat- ment	pH	有机质 Soil organic matter ($\text{g}\cdot\text{kg}^{-1}$)	全氮 Total nitrogen ($\text{g}\cdot\text{kg}^{-1}$)	铵态氮 Ammonium nitrogen ($\text{mg}\cdot\text{kg}^{-1}$)	硝态氮 Nitrate nitrogen ($\text{mg}\cdot\text{kg}^{-1}$)	有效磷 Available phosphorus ($\text{mg}\cdot\text{kg}^{-1}$)	速效钾 Available potassium ($\text{mg}\cdot\text{kg}^{-1}$)	可溶性有机碳 Dissolved organ- ic carbon ($\text{mg}\cdot\text{kg}^{-1}$)	可溶性有机氮 Dissolved organic nitrogen ($\text{mg}\cdot\text{kg}^{-1}$)
CK	6.16±0.10ab	26.0±1.45cd	1.66±0.04b	6.22±0.17d	55±5.63f	42.3±0.66b	380±30.0d	83±7.54b	77±39.4d
F_{100}	6.26±0.03a	25.5±1.40d	2.06±0.03a	7.66±0.48d	66±13.60ef	43.3±2.08b	412±6.0cd	81±4.51b	76±19.4d
$F_{70}G_{0.5}$	6.00±0.09bc	28.6±1.43bcd	2.10±0.04a	8.62±1.39d	121±7.04bcd	44.6±4.65ab	653±81.9ab	112±9.33a	185±12.2bc
$F_{70}G_{1.0}$	6.03±0.01bc	28.9±0.58abcd	2.06±0.12a	14.50±1.00c	140±15.60bc	45.9±2.94ab	583±18.6abc	103±3.02a	191±20.3bc
$F_{70}G_{1.5}$	5.95±0.08c	29.2±1.52abcd	2.09±0.15a	18.40±1.02b	101±12.50cde	47.7±3.26ab	625±60.6ab	111±4.58a	221±18.0ab
$F_{70}G_{2.0}$	5.95±0.07c	32.7±1.43a	2.17±0.11a	22.60±2.73a	104±18.70cde	50.1±1.31ab	660±48.1ab	113±14.00a	259±13.4a
$F_{85}G_{0.5}$	6.12±0.03abc	29.5±0.81abc	2.13±0.07a	7.50±0.05d	90±5.26def	42.2±2.83b	478±91.4bcd	103±5.84a	136±13.4cd
$F_{85}G_{1.0}$	5.99±0.05bc	30.6±1.17ab	2.01±0.04a	6.55±0.33d	143±21.30bc	45.9±6.35ab	503±58.6abcd	112±6.78a	228±18.5ab
$F_{85}G_{1.5}$	6.01±0.03bc	31.8±1.63ab	1.90±0.19ab	14.10±1.40c	151±13.50b	46.5±0.95ab	590±115.0abc	116±3.00a	209±20.7ab
$F_{85}G_{2.0}$	6.01±0.09bc	32.4±1.33ab	1.99±0.06a	6.93±0.61d	250±22.40a	52.9±1.10a	678±81.9a	117±3.37a	242±19.0ab

注: 表中数值为平均值±标准误差($n=3$)。同列不同小写字母表示处理间差异显著($P<0.05$), 下同。

Note: The values in the Table represent the mean ± standard error ($n=3$). Different lowercase letters in the same column indicate significant differences among treatments ($P<0.05$), the same below.

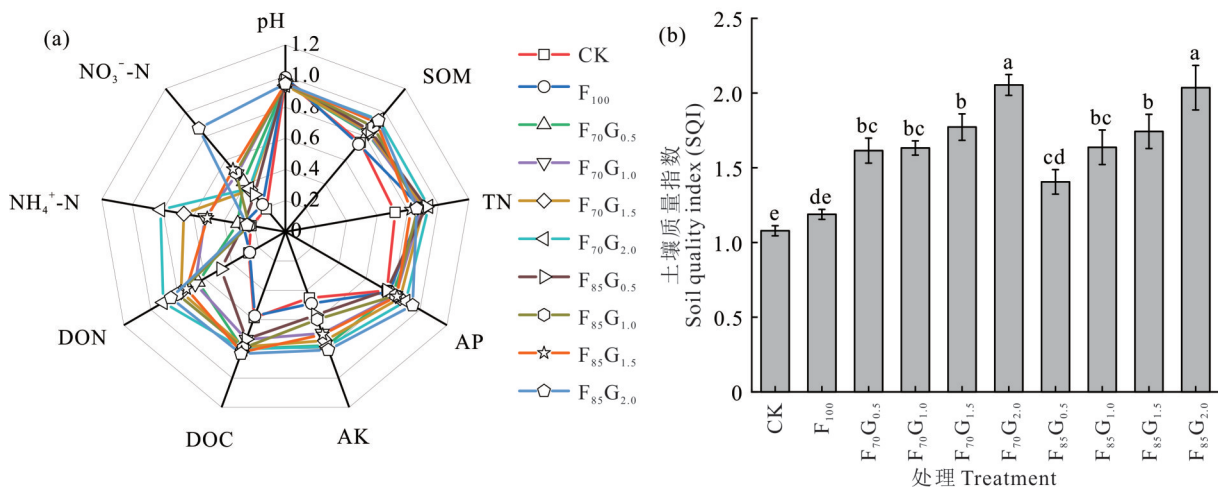


图 2 土壤养分性状及土壤质量指数

Fig. 2 Soil nutrients and soil quality index

pH: 土壤 pH 值; $\text{NO}_3^-\text{-N}$: 硝态氮; $\text{NH}_4^+\text{-N}$: 铵态氮; DON: 可溶性有机氮; DOC: 可溶性有机碳; AK: 速效钾; AP: 有效磷; TN: 总氮; SOM: 土壤有机质。下同。pH: Soil pH value; $\text{NO}_3^-\text{-N}$: Nitrate nitrogen; $\text{NH}_4^+\text{-N}$: Ammonium nitrogen; DON: Dissolved organic nitrogen; DOC: Dissolved organic carbon; AK: Available potassium; AP: Available phosphorus; TN: Total nitrogen; SOM: Soil organic matter. The same below.

2.3 土壤酶活性

相比冬闲处理, 种植翻压绿肥配合减施氮肥增加了土壤水解酶活性(表 3)。相比 F_{100} 处理, $F_{70}G_{2.0}$ 和 $F_{85}G_{2.0}$ 处理土壤 β -葡萄糖苷酶、 β -纤维二糖苷酶活性分别显著提升了 45.2%、49.5% 和 29.9%、50.5%。绿肥翻压 15000~30000 $\text{kg}\cdot\text{hm}^{-2}$, 减施氮肥 15% 和 30% 条件下土壤 β -木糖苷酶活性分别提升 124%~225% 和 85.7%~

230.5%。翻压绿肥配合减施氮肥 15% 处理 α -葡萄糖苷酶活性较 F_{100} 提高了 40.1%~147.8%。绿肥翻压 22500 和 30000 $\text{kg}\cdot\text{hm}^{-2}$ 配合减施氮肥 30% 处理 α -葡萄糖苷酶活性分别提高了 62.7% 和 90.8%。相比 F_{100} 处理, $F_{70}G_{2.0}$ 、 $F_{85}G_{1.5}$ 和 $F_{85}G_{2.0}$ 处理土壤乙酰氨基葡萄糖苷酶活性分别提高了 48.1%、20.8% 和 58.5%, 亮氨酸氨基肽酶活性分别提高了 19.7%、15.3% 和 34.2%。碱性磷酸酶活性随着绿肥翻压量的增加而递增, 相比 F_{100} 、 $F_{70}G_{2.0}$ 和 $F_{85}G_{2.0}$ 分别显著增加 37.8% 和 24.8%。

表 3 不同施肥处理土壤水解酶活性

Table 3 Hydrolase enzyme activities in soils under different treatments ($\text{nmol}\cdot\text{h}^{-1}\cdot\text{g}^{-1}$)

处理 Treat- ment	碳转化相关酶 Carbon-related enzyme activities				氮转化相关酶 Nitrogen-related enzyme activities		磷转化相关酶 Phosphorus-related enzyme activities
	β -葡萄糖苷酶 β -glucosidase	β -纤维二糖苷酶 β -cellobiosidase	β -木糖苷酶 β -xylosidase	α -葡萄糖苷酶 α -glucosidases	乙酰氨基葡萄糖 苷酶 Acetylglu- cosaminidase	亮氨酸氨基 肽酶 Leucine aminopeptidase	碱性磷酸酶 Alkaline phosphatase
CK	26.5±1.72bc	1.62±0.16c	2.51±0.27d	0.96±0.07f	7.6±0.25e	514±9.57d	509±20.3f
F_{100}	28.1±0.86b	1.82±0.24bc	2.62±0.41d	1.42±0.22ef	10.6±0.74cd	568±8.24cd	606±11.4cde
$F_{70}G_{0.5}$	24.2±1.33bc	1.75±0.11bc	3.39±0.13d	1.52±0.11e	7.9±0.31e	534±8.33d	534±11.6ef
$F_{70}G_{1.0}$	28.7±1.64b	2.19±0.07abc	4.84±0.44c	1.87±0.04de	9.2±0.30de	564±4.32cd	580±9.9def
$F_{70}G_{1.5}$	36.6±2.50a	2.24±0.14abc	6.86±0.15b	2.31±0.02cd	11.6±0.90bc	616±7.99bc	645±39.4cd
$F_{70}G_{2.0}$	40.8±3.91a	2.72±0.07a	8.66±0.47a	2.71±0.13bc	15.7±1.05a	680±20.40b	835±30.4a
$F_{85}G_{0.5}$	20.9±3.23c	1.94±0.06bc	3.41±0.46d	1.99±0.02d	7.9±0.91e	520±0.88d	630±36.0cd
$F_{85}G_{1.0}$	29.8±0.52b	2.33±0.17ab	5.86±0.26bc	2.22±0.04d	12.5±0.49bc	579±28.60cd	666±4.4c
$F_{85}G_{1.5}$	30.1±0.74b	2.72±0.52a	5.95±0.56b	2.91±0.18b	12.8±0.31b	655±17.90b	675±13.5bc
$F_{85}G_{2.0}$	36.5±0.98a	2.74±0.13a	8.52±0.13a	3.52±0.37a	16.8±0.79a	762±64.50a	756±54.8ab

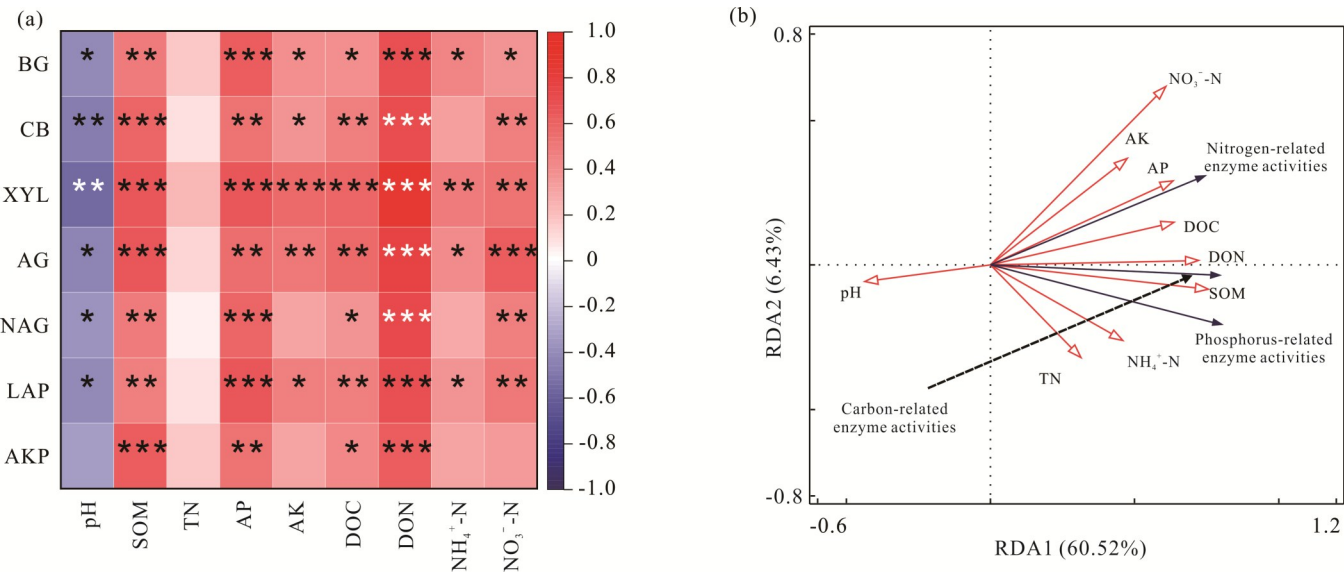


图 3 相关性和冗余分析

Fig. 3 The correlation and redundancy analysis (RDA)

BG: β -葡萄糖苷酶; CB: β -纤维二糖苷酶; XYL: β -木糖苷酶; AG: α -葡萄糖苷酶; NAG: 乙酰氨基葡萄糖苷酶; LAP: 亮氨酸氨基肽酶; AKP: 碱性磷酸酶。Nitrogen-related enzyme activities: 氮转化相关酶活性; Carbon-related enzyme activities: 碳转化相关酶活性; Phosphorus-related enzyme activities: 磷转化相关酶活性。*表示 $P<0.05$, **表示 $P<0.01$, ***表示 $P<0.001$ 。下同。BG: β -glucosidase; CB: β -cellobiosidase; XYL: β -xylosidase; AG: α -glucosidase; NAG: Acetylglucosaminidase; LAP: Leucine aminopeptidase; AKP: Alkaline phosphatase. *: $P<0.05$, **: $P<0.01$, ***: $P<0.001$. The same below.

2.4 土壤养分性状、酶活性与产量间的关系

土壤养分性状和酶活性的相关性分析结果表明(图 3a),土壤有机质、有效磷、可溶性有机碳、可溶性有机氮均与土壤碳氮磷转化酶活性呈显著正相关,土壤 pH 与碳氮转化相关酶活性显著负相关,土壤硝态氮与碳氮转化相关酶活性显著正相关。冗余分析结果表明(图 3b),9 种养分性状对土壤酶活性的解释率为 66.95%(RDA1 为 60.52%,RDA2 为 6.43%),土壤有机质和有效磷的箭头连线较长,可知两者对土壤酶活性的变化起到很好解释作用,贡献率分别为 51.7% 和 24.0%(表 4)。采用偏最小二乘路径模型揭示不同因子对烤烟产量的影响(图 4a),因子载荷分析表明土壤无机氮和 α -葡萄糖苷酶(或乙酰氨基葡萄糖苷酶)可分别作为反映土壤有效养分和酶活性的有力指标。试验处理显著影响土壤 pH 值、总氮和土壤酶活性,土壤有机质(0.48)和酶活性(0.41)显著影响烤烟产量(图 4a)。随机森林结果表明(图 4b),土壤养分性状中硝态氮和可溶性有机氮对烟草产量的贡献率较高。

表 4 冗余分析参数

Table 4 Redundancy analysis parameters (%)

处理 Treatment	有机质 Soil organic matter	有效磷 Available phosphorus	pH	可溶性有机氮 Dissolved organic nitrogen	硝态氮 Nitrate nitrogen	速效钾 Available potassium	全氮 Total nitrogen	可溶性有机碳 Dissolved organic carbon	铵态氮 Ammonium nitrogen
解释率 Explains rate	34.6	16.1	3.8	5.1	4.5	1.1	0.8	0.5	0.5
贡献率 Contribution rate	51.7	24.0	5.7	7.7	6.7	1.6	1.2	0.7	0.7
显著性 Significance	**	**	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.

注: n. s. 表示无显著性差异。**表示 $P < 0.01$ 。

Note: n. s. indicate no significant difference ($P > 0.05$). ** indicate $P < 0.01$.

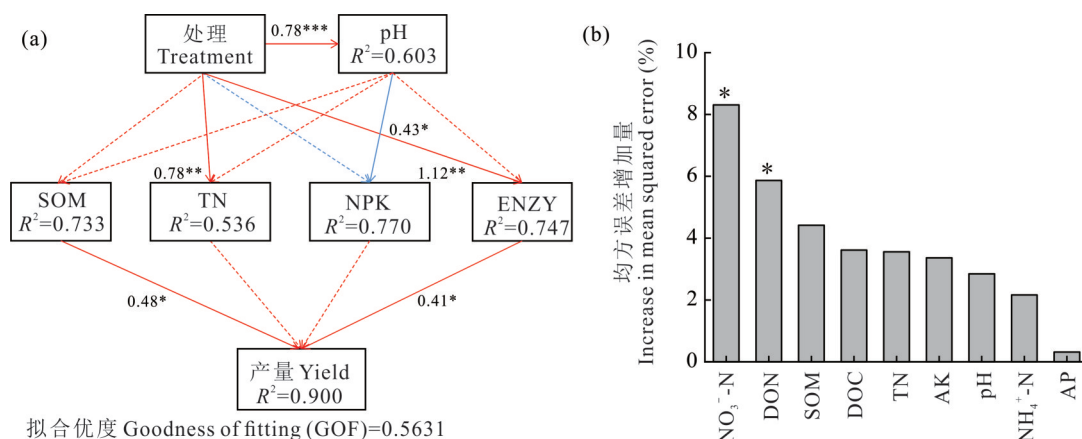


图 4 偏最小二乘路径和随机森林模型

Fig. 4 The partial least squares path model and random forest model

NPK 表示无机氮、有效磷和速效钾,因子载荷值分别为 0.813、0.478 和 0.794,ENZY 表示土壤 BG、CB、XYL、AG、NAG、LAP 和 AKP 活性,因子载荷值分别为 0.752、0.780、0.824、0.946、0.912、0.907 和 0.886。NPK represents inorganic nitrogen, available phosphorus, and available potassium, with factor loadings of 0.813, 0.478, and 0.794, respectively. ENZY represents soil enzyme activities of BG, CB, XYL, AG, NAG, LAP, and AKP, with factor loadings of 0.752, 0.780, 0.824, 0.946, 0.912, 0.907, and 0.886, respectively.

3 讨论

3.1 绿肥配施减量氮肥提高土壤质量和烤烟产量

施肥方式对土壤养分性状影响各异,减施氮肥下绿肥还田能够提高土壤养分含量^[20]。本研究表明,与常规施肥相比,种植翻压光叶紫花苕配合减施 15% 化肥和翻压 30000 kg·hm⁻² 绿肥配合减施 30% 化肥显著提高了土壤

有机质含量($P < 0.05$),但对全氮含量影响不显著($P > 0.05$),然而土壤可溶性有机氮和硝态氮含量大幅提升,且随着绿肥翻压量的增加不断增加,说明种植利用绿肥能替代部分氮肥,减少化学氮投入,同时提高活性氮含量^[21]。前人研究同样发现绿肥与化肥配施可以培育土壤碳氮库,改善土壤养分性状^[22]。绿肥还田对土壤有机质的提升是多方面的,一方面绿肥自身积累的大量有机物质为土壤微生物提供丰富的碳源;另一方面可增加土壤微生物生物量,促进微生物对有机物质的分解;同时改善土壤结构促进土壤团聚体形成,提高土壤有机质稳定性^[23]。氮肥减施可减少氮肥对土壤氮的负面影响(土壤酸化、有机质矿化加速等)^[24],绿肥还田则通过微生物矿化分解,缓慢释放氮,从而增加土壤活性氮含量^[25-26]。另外,光叶紫花苜蓿能够发挥生物固氮作用,翻压后亦可为土壤提供氮素,增加土壤速效养分含量^[18]。相比常规施肥,化肥减量30%翻压光叶紫花苜蓿7500~30000 kg·hm⁻²均显著提高土壤质量指数,其中,F₇₀G_{2.0}处理下土壤质量指数最高,说明化肥减量30%翻压光叶紫花苜蓿能够有效提高烟田土壤综合肥力。

烤烟对环境条件极为敏感,因此土壤养分的充足供应对于提高烤烟产量至关重要^[10]。相比常规施肥,减施氮肥30%条件下,翻压22500~30000 kg·hm⁻²绿肥,烤烟产量显著增加,主要是由于不同施肥方式对养分供应的影响各异。PLS-PM模型分析表明,不同翻压量绿肥通过调节土壤有机质和酶活性($P < 0.05$)影响烤烟产量,表明土壤有机质含量和酶活性的提高对烤烟产量具有正面影响。翻压绿肥提高了土壤有机质含量,有助于改善土壤物理结构,如增加土壤孔隙度,为作物根系的生长提供良好的环境^[27]。另外,土壤有机质在微生物作用下分解,释放出植物生长所需的养分,有助于提高作物的养分利用效率、促进其生长^[28]。翻压绿肥后,土壤酶活性的改善标志着土壤中生物过程更加活跃,不仅利于土壤有机物的分解转化,还确保了烤烟生长所需的营养元素供应,有助于提升烤烟产量^[29]。王亚麒^[4]同样发现冬季种植绿肥,可能改变烟田土壤微生物的生长环境,有益于缓解烤烟连作障碍,维持烤烟产量。土壤速效养分中无机氮在PLS-PM模型中因子载荷值最高,运用随机森林分析发现,土壤硝态氮和可溶性有机氮对烟草产量的贡献率较大,进一步表明光叶紫花苜蓿主要通过改善土壤活性氮含量来促进作物生长^[30]。因此,绿肥与减量化肥配施有利于加速土壤养分循环,这也是烤烟产量提高的重要因素。根据2022年K326品种烤烟的均价、投入的光叶紫花苜蓿种子成本及30%的节肥效益^[31],经成本核算,翻压光叶紫花苜蓿22500和30000 kg·hm⁻²配合减施30%氮肥的烟叶产量增收和节肥效益为2784和3127元·hm⁻²,大于种植绿肥的成本(1100和1467元·hm⁻²),表明,光叶紫花苜蓿与减量化肥配施不仅能够实现节肥增收,而且经济效益显著。

3.2 绿肥配施减量氮肥提高土壤酶活性

土壤酶活性是衡量土壤肥力和生物活性的关键指标,反映土壤中有机物质的分解和营养循环的活跃程度^[32]。植物残体分解物和土壤微生物的代谢产物是土壤酶的主要贡献者^[33]。绿肥还田为土壤微生物的生长和发育提供了丰富的底物,不仅促进了微生物的代谢活动,也显著提高了土壤中与碳、氮、磷养分循环相关的水解酶活性^[34]。本研究发现,与常规施肥相比,翻压绿肥并配合氮肥减施,显著促进了参与土壤中碳、氮、磷转化相关酶的活性,同时,随着绿肥翻压量的增加酶活性逐渐提升。王慧等^[20]同样发现,相比常规施肥,紫云英(*Astragalus sinicus*)绿肥还田配合减施20%和40%常规量氮肥处理下,南方稻田土壤 α -葡萄糖苷酶、 β -纤维二糖苷酶、 β -葡萄糖苷酶和 β -木糖苷酶活性显著提高。

种植翻压绿肥能够通过改变土壤全量和速效养分来影响土壤水解酶活性^[35]。减施氮肥条件下,随着绿肥翻压量的增加,土壤水解酶活性呈上升趋势,这可能是由于绿肥不仅直接增加了土壤中的全量碳氮含量,还通过有机物的分解提高了碳和氮的可用性,改变了微生物群落结构,从而促进了微生物的生长和活性^[36]。微生物活动是土壤酶产生和活性维持的重要驱动力,微生物在分解有机物过程中促进多种酶类产生,这些酶类是土壤中酶活性增加的关键因素^[14]。相关性分析表明,土壤pH与土壤碳氮转化酶活性显著负相关,表明绿肥还田配施减量氮肥通过负向调节土壤pH,有助于提升参与碳氮转化的水解酶活性。与叶协锋等^[29]的研究结果一致,土壤有机碳和速效养分均在不同程度上与酶活性呈现一定正相关关系,其中土壤有机质和有效磷对酶活性的贡献较大。烟田土壤微生物易受到碳、磷限制^[18],而绿肥还田配施减量氮肥提升了土壤有机质和有效磷含量,有助于缓解土壤微生物碳、磷限制^[18],提高土壤养分利用效率和作物生产力。因此,绿肥还田配合减量化肥有助于提高土壤酶活

性、改善微生物环境。其中,种植翻压光叶紫花苕 22500~30000 kg·hm⁻²配合减施 30% 氮肥综合效果更好。

4 结论

与常规施肥相比,光叶紫花苕翻压配合减施 30% 氮肥可显著提高土壤中参与碳氮磷转化相关水解酶的活性,改善土壤养分,增加土壤质量指数,从而提升烤烟产量,本试验条件下以光叶紫花苕翻压量 22500~30000 kg·hm⁻²的综合效果更优。

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