

DOI: 10.3724/SP.J.1006.2011.01650

氮肥运筹和栽培方式对杂交籼稻 II 优 498 结实期群体光合特性的影响

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摘 要: 以杂交籼稻 II 优 498 为材料, 在温江和汉源两种生态条件下, 研究了不同氮肥运筹方式对宽窄行、三角形、扩行减株稀植和抛秧 4 种栽培方式水稻结实期群体光合生产的影响。结果表明, 随穗肥施用比例的增加, 结实期冠层透光特性得到改善, 抽穗期茎鞘干重、高效叶面积率和有效叶面积率等群体质量指标得到提高, 抽穗后叶面积指数(LAI)和呼吸占群体光合的相对比例(CR/TCAP)有所降低, 而群体光合速率(CAP)在两地的变化趋势并不一致, 温光条件较差的温江点表现为先升后降, 而温光条件较好的汉源点则呈下降趋势。当氮肥运筹为 6:3:1 时, 宽窄行和三角形栽培有利于改善冠层透光特性和群体质量, CAP 升高的同时结实中后期 CR/TCAP 增幅减小, 群体光合生产能力得到提高; 当氮肥运筹比例为 5:2:3 时, 扩行减株稀植栽培透光性能和群体质量的增幅最大, CAP 升高的同时 CR/TCAP 并未增加甚至有所减少, 群体光合生产能力高于其他栽培方式; 当氮肥运筹比例为 4:1:5 时, 抛秧栽培在温江点有利于改善群体质量和增加光能截获, 结实中后期 CAP 显著提高的同时 CR/TCAP 降低, 群体光合生产优势明显, 但温光条件改善后此优势并无体现。因此, 提高水稻群体光合生产能力需结合当地温光条件并针对栽培方式采用适宜的氮肥管理措施。

关键词: 生态条件; 栽培方式; 氮肥运筹; 冠层特性; 群体光合生产

Effects of Nitrogen Application Strategy and Cultivation Model on the Performances of Canopy Apparent Photosynthesis of *Indica* Hybrid Rice Eryou 498 during Filling Stage

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Abstract: A field experiment was conducted at Wenjiang and Hanyuan using *indica* hybrid rice Eryou 498. With the cultivation models including wide-narrow row spacing cultivation, triangle cultivation, spreading planting by expanding row spacing and reducing plant space, scattered planting cultivation. The results indicated that with the increase of N application at booting stage, canopy light transmittance performance improved, population quality index including single stem and sheath weight in heading, the ratio of leaf area of productive tillers and ratio of leaf area from flag leaf to 3rd leaf from top of productive tillers increased, leaf area index (LAI) and ratio of canopy respiration to total canopy apparent photosynthesis (CR/TCAP) decreased slightly, canopy apparent photosynthesis (CAP) increased first and decreased afterwards at Wenjiang, but showed decreasing trend at Hanyuan. When nitrogen fertilizer was applied at 60% before transplanting, 30% at tillering, and 10% at booting, it was beneficial to improving canopy light transmittance performance and population quality for wide-narrow row spacing cultivation and triangle cultivation, their CAP increased on the premise of no increasing in CR/TCAP, their ability of photosynthetic production improved at last. When nitrogen fertilizer was applied at 50% before transplanting, 30% at tillering, and 20% at booting, the increasing range of canopy light transmittance performance and population quality for spreading planting by expanding row spacing and reducing plant space was greater than that of other cultivation models, its CAP was higher than that of other cultivation models, but CR/TCAP did not increase at the same time, even decreased somewhat, so its capacity of photosynthetic production was higher than that of other cultivation models. When nitrogen fertilizer was applied at 40% before transplanting, 10% at tillering,

本研究由国家粮食丰产科技工程项目(2006BAD02A05)和四川省农业产业体系建设项目资助。

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Received(收稿日期): 2010-12-28; Accepted(接受日期): 2011-05-27; Published online(网络出版日期): 2011-06-28.

URL: <http://www.cnki.net/kcms/detail/11.1809.S.20110628.1008.011.html>

and 50% at booting, scattered planting cultivation was propitious to improving population quality and interception of light, it had obvious advantages in photosynthetic production by increasing CAP during middle-late period of filling stage and decreasing CR/TCAP, but there was no advantage in photosynthetic production if temperature and light conditions was improved. From above, it was suggested that improving capacity of photosynthetic production should adopt suitable nitrogen application strategy according to ecological condition and cultivation model.

Keywords: Ecological condition; Cultivation models; Nitrogen application strategy; Canopy characteristics; Photosynthetic production

籽粒灌浆物质的 90%左右来自抽穗以后的光合同化物^[1], 提高抽穗后群体光合生产能力是实现水稻增产的关键^[2], 就如何提高水稻抽穗后群体光合能力, 前人从株叶形态、冠层透光特性及群体质量等方面作了广泛研究^[3-5]。其中, 马均等^[6]提出重穗型杂交稻剑叶叶角小而挺直, 倒二、三叶叶角顺次适当增大, 形成宝塔形的叶层结构, 有利于形成比较理想的受光姿态, 截获更多的太阳光能, 提高光能利用率; 刘建丰等^[7]认为, 超高产杂交稻是在一定量的 LAI 基础上减小叶片角度和增长剑叶长度, 从而增加群体透光率、降低消光系数, 实现群体光合速率提高的; 赵全志等^[8]认为群体光合效率的提高必须以抽穗期高质量的群体为前提。由此可见, 冠层特性、群体光合生产与抽穗期群体质量间存在必然的联系, 但其相关研究主要集中在品种上, 栽培技术方面涉及甚少。宽窄行栽培、三角形栽培、扩行减株稀植栽培及抛秧栽培作为四川水稻的主要生产技术, 植株田间分布形式的不同导致其冠层透光特性产生差异^[9-10], 抽穗后叶片光合能力也随之不同^[11-12]。氮素是影响水稻生长发育最为活跃因素之一^[13], 其运筹方式的改变对群体质量影响甚大^[14], 合理的氮肥运筹方式是提高水稻群体质量, 实现产量大幅提高的有效途径^[2], 因而不同氮肥运筹对上述栽培方式冠层特性及群体光合生产影响值得进一步研究。

此外, 不同生态区域水稻株叶形态、冠层透光特性不同^[15], 且生态条件改变后高产群体对水稻冠层形态结构和光合生理特性的要求也相应变化^[7]。温江位于成都平原, 光照不足、温差小、湿度大, 水稻生长中后期常有阴雨天气, 是制约水稻高产的限制因素之一; 汉源地处四川西南山区, 光照资源丰富, 其水稻产量可达 15 t hm⁻², 2 个地区的光热资源差异造成水稻产量潜力差异很大^[16]。因此, 研究温江和汉源两地氮肥运筹和栽培方式对结实期群体光合生产的影响, 有利于深入了解结实期冠层特性、群体质量及群体光合生产三者间的关系, 探索提高水稻群体光合生产能力的关键因素, 为水稻高产栽培提供科学依据。

1 材料与方法

1.1 试验设计

2010 年分别在四川省成都市温江区四川农业大学水稻研究所试验田和四川省汉源县九襄镇大庄村种植杂交稻 II 优 498。两地前茬均为大蒜, 土壤质地为沙壤土, 两地土壤养分含量差异并不明显(表 1), 但水稻生长期气候特点差异较大(表 2), 主要表现为温江点日照时数短、太阳总辐射量小, 而汉源光照时数长、太阳总辐射量大。

采用二因素裂区试验设计, 以氮肥运筹方式为主区, 设 3 个处理, 底、蘖、穗肥比例分别为 6:3:1

表 1 温江和汉源土壤养分含量
Table 1 Nutrient content of soil at Wenjiang and Hanyuan

地点 Location	有机质 Organic matter (g kg ⁻¹)	速效氮 Available N (mg kg ⁻¹)	速效磷 Available P (mg kg ⁻¹)	速效钾 Available K (mg kg ⁻¹)	全氮 Total N (g kg ⁻¹)	全磷 Total P (g kg ⁻¹)	全钾 Total N (g kg ⁻¹)
四川温江 Wenjiang, Sichuan	26.99	97.31	60.95	49.97	1.56	0.246	13.51
四川汉源 Hanyuan, Sichuan	21.56	103.19	65.68	42.76	1.73	0.260	14.04

表 2 温江和汉源 3~9 月份气象资料
Table 2 Meteorological data from March to September at Wenjiang and Hanyuan

地点 Location	海拔高度 Altitude (m)	平均气温 Average temperature (°C)	日照时数 Light time (h)	太阳总辐射量 Gross solar radiation (J m ⁻¹)	降雨量 Precipitation (mm)
四川温江 Wenjiang, Sichuan	530	20.1	360	2253	931.6
四川汉源 Hanyuan, Sichuan	1000	19.8	673	3015	739.0

(N1)、5:2:3 (N2)、4:1:5 (N3); 以栽培方式为副区, 设4种栽培方式, 分别为宽窄行栽培(A1), 插栽密度为 18×10^4 株 hm^{-2} , 插栽规格为 $(40+26.7) \text{ cm} \times 16.7 \text{ cm}$; 三角形栽培(A2), 插栽密度 18.75×10^4 株 hm^{-2} , 插栽规格为 $40 \text{ cm} \times 40 \text{ cm}$, 排行错窝, 每穴按三角形栽3苗, 穴内3株株距10 cm; 扩行减株稀植栽培(A3), 插栽密度为 18×10^4 株 hm^{-2} , 插栽规格为 $33.3 \text{ cm} \times 16.7 \text{ cm}$; 抛秧栽培(A4), 抛栽密度为 18×10^4 株 hm^{-2} 。小区面积为 15.0 m^2 , 3次重复, 小区间隔30 cm, 重复间隔50 cm, 小区间作埂覆膜。

温江点播种、移栽和收获日期分别为4月2日、5月11日和9月7日, 汉源点分别为3月25日、5月9日和9月16日。试验总氮用量为 180 kg hm^{-2} , 氮、磷、钾配比2:1:2, 磷肥全作底肥, 钾肥底、穗肥比例2:1, 分蘖肥于移栽后7 d施用, 穗肥于拔节后15 d施用。A1、A3、A4处理分蘖前期田间保持2~3 cm水层, 无效分蘖期排水晒田, 穗分化期淹水3 cm左右, 抽穗后干湿交替灌溉; A2处理从移栽至分蘖后期水分管理为灌水1 cm左右, 让其自然落干至田间无水层后再灌水1 cm左右, 如此循环, 无效分蘖期排水晒田, 从拔节至抽穗期, 田间保持1~2 cm水层, 以后干湿交替灌溉至成熟前7 d排干水。此外, 其余田间管理措施各处理均保持一致。

1.2 取样与测定方法

1.2.1 干物质和叶面积指数(LAI) 分别于抽穗期和抽穗后15 d、30 d每小区选取有代表性植株5株, 采用长宽系数法测定剑叶、倒二、倒三叶和下部叶片绿叶面积, 之后分植株部位烘干称重。

1.2.2 上部叶片叶基角 于齐穗后10 d, 在田间每小区选取生长基本一致的10株, 选定主茎, 分别测定剑叶、倒二和倒三叶叶基角。

1.2.3 消光系数(k) 分别于抽穗期和抽穗后15 d、30 d采用美国LI-COR公司生产的LI-191SA线性光量子传感器和LI-250棍式光照计, 选择晴天的11:00~13:00, 分别测定每小区冠层内(地表)及冠层顶部入射光合辐射强度。A1、A2、A3处理每小区选取3点按十字线形式分别在相邻2行间测定冠层内光合辐射强度平均值, A4处理在小区对角线上选取5点按十字线形式测定取平均值, 计算消光系数(k)。

1.2.4 群体光合(CAP)和群体呼吸速率(CR) 采用董树亭等^[17]方法并略作改进。于开花期、灌浆期和乳熟期选择晴天无云天气, 温江、汉源点光强分别稳定在 $1\ 000 \sim 1\ 200 \mu\text{mol m}^{-2} \text{ s}^{-1}$ 和 $1\ 400 \sim 1\ 600$

$\mu\text{mol m}^{-2} \text{ s}^{-1}$ 时, 用GXH-305型红外线 CO_2 分析仪在田间直接测定群体光合速率。同化箱长1.2 m, 宽0.8 m, 高1.5 m, 箱内用2台鼓风机搅拌气体, 框架外罩透明聚酯薄膜。采用闭路系统, 重复3次, 每次测定同化箱内株数均为18株, A1和A3处理测定3行, 每行6株, A2处理测定3行, 每行2穴, A4处理每次测定时先划定区域确定株数然后进行测定, 确保同化箱内测定植株株数一致, 测定60 s。用遮光布罩遮光后, 测定群体呼吸速率。在群体结构相近的田地上, 剪去与同化箱底大小相同面积地表上的植株后, 测定土壤呼吸释放的 CO_2 , 测定方法同群体光合速率, 以修正群体光合和群体呼吸的测定值。

1.2.5 单位面积穗数和产量测定 于成熟期每小区调查30株, 计算单位面积穗数, 收获时除去四周边及杂株按实收面积计产。

1.2.6 计算方法 消光系数(k)= \ln (入射光合辐射强度/冠层内(地表)光合辐射强度)/LAI; 呼吸占群体总光合的相对比例, 即 $\text{CR}/\text{TCAP}=\text{CR}/(\text{CR}+\text{CAP}) \times 100\%$ 。

用DPS软件进行试验数据方差分析, 用最小显著差法LSD检验平均数。

2 结果与分析

2.1 群体光合生产

由表3可知, 汉源点各时期群体光合速率(CAP)显著高于温江点, 抽穗期及抽穗后15 d群体呼吸速率(CR)与温江点差异不显著, 抽穗后30 d显著高于温江点, 群体呼吸占群体光合的相对比例(CR/TCAP)在抽穗期及抽穗后15 d显著低于温江点, 抽穗后30 d两地CR/TCAP相当。不同氮肥运筹方式N1和N2处理间, CAP、CR随测定时期和生态条件的改变互有高低, 但均高于N3处理, CR/TCAP则随氮肥后移程度的增加而减少。随氮肥运筹方式的改变, 在N1处理下A1、A2处理CAP高于A3、A4处理, 且其CR/TCAP在结实中后期的增幅更小; 在N2处理下A3处理各时期CAP在各栽培方式间最高, 其CR/TCAP比A1、A2处理更低, 而比A4处理在温江点和汉源点分别更低和更高; 在N3处理下A4处理在温江点各时期CAP高于其他栽培方式, 且CR/TCAP最低, 而在汉源点其结实中前期CR/TCAP虽显著低于其他栽培方式, 但CAP的优势并无体现。这表明各栽培方式群体光合生产在不同氮肥运筹方式下存在差异, 并受生态条件影响。

2.2 群体质量、有效穗数和籽粒产量

表 4 表明, 汉源点抽穗期各群体质量指标、有效穗数及产量极显著高于温江点。随氮肥后移程度的增加, 温江点各群体质量指标均呈增加趋势, 籽粒产量则表现为先增加后降低; 汉源点抽穗期茎鞘重和有效叶面积率呈增加趋势, 而高效叶面积率、抽穗至成熟期干物质积累量以及籽粒产量均表现为先增加后降低; 两地有效穗均呈降低趋势。从不同栽培方式看, N1 处理下, A1 和 A2 处理抽穗期各群体质量指标及籽粒产量均高于 A3 和 A4 处理; N2 处理下, 各栽培方式处理抽穗期各群体质量指标及籽粒产量均以 A3 处理为最高; N3 处理下, 温江点抽穗期茎鞘重表现为 A1 和 A3 处理高于 A2 和 A4 处理, 有效叶面积率和高效叶面积率栽培方式间无显著差异, 抽穗至成熟期干物质积累量及籽粒产量则以 A4 处理最高, 而汉源点 A1、A3 和 A4 处理抽穗期各群体质量指标及籽粒产量无显著性差异, 但均不同程度地高于 A2 处理。此外, 有效穗数总体而言以 A4 处理最高。

相关分析表明, 高效叶面积率与抽穗后各时期 CR/TCAP 均呈负相关关系, 温江点抽穗期、抽穗后 15 d 和 30 d 相关系数分别为 -0.6876^* 、 -0.6117^* 、 -0.7684^{**} , 均达显著以上水平($r_{0.01,10} = 0.576$, $r_{0.01,10} = 0.708$), 汉源点相关系数分别为 -0.2629 、 -0.4281 、 -0.2035 , 均未达显著水平。这表明高效叶面积率的提高有利于降低 CR/TCAP, 将更多的光合产物用于物质积累, 尤其是在温光条件较差的温江。

2.3 两种生态条件下不同氮肥运筹方式对抽穗后各时期叶面积指数(LAI)和消光系数(k)的影响

从表 5 可见, 汉源点各时期叶面积指数(LAI)极显著高于温江点, 随氮肥后移程度的增加抽穗期及抽穗后 15 d 的 LAI 显著下降, 但抽穗后 30 d 的 LAI 氮肥运筹方式间无显著差异。各栽培方式间, 抽穗期的 LAI 以 A4 处理最高, 抽穗后 15 d 的 LAI 在温江点和汉源点分别以 A4 和 A2 处理最高, 抽穗后 30 d 的 LAI 在 N1 处理下表现为 A1、A2 处理高于 A3、A4 处理, N2、N3 处理下则相反。

各时期消光系数(k)表现为汉源点显著小于温江点, 随氮肥后移程度的增加各时期 k 值呈减小趋势, 栽培方式间抽穗后各时期 k 值表现为 A4 处理不同程度地高于其他栽培方式, 可见其群体遮蔽性高于其他栽培处理。 k 值消除了 LAI 对冠层透光的影响, 因此宽窄行栽培和三角形栽培结实中后期抽穗后更高

的冠层通透性主要源自其植株田间配置方式, 而并非 LAI 的减少。

2.4 叶片形态

表 6 表明, 温江点上三叶叶片长度、宽度和叶基角均显著高于汉源点, 而比叶重显著低于汉源点。随氮肥后移程度的增加, 比叶重及叶基角均随之增加, 上三叶大小温江点趋于增加, 而汉源点倒二、倒三叶趋于减小。从栽培方式看, 温江点剑叶长度在栽培方式间无显著差异, A1、A2、A3 倒二叶、倒三叶长度随氮肥运筹方式的改变互有高低, 但均显著高于 A4 处理, 上三叶宽度以 A2 处理最高, 汉源点除倒三叶长度 A1、A2 处理更高外, 其余上三叶长度、宽度无显著差异; 上三叶叶基角表现为 A2 处理显著低于其他栽培方式处理; 比叶重在栽培方式和氮肥运筹方式间互作效应极显著, N1 处理下表现为 A1、A2 处理显著高于 A3、A4 处理, N2 处理下以 A3 处理最高, N3 处理下各栽培方式间无显著性差异。

3 讨论

3.1 水稻冠层特性

叶片形态是株型的重要组成部分, 合理的株型可以通过对冠层结构的改造而影响冠层内的辐射传输, 协调光合积累与呼吸消耗的关系, 提高光能综合利用效率^[18], 对高产水稻上部三叶的长、宽、厚以及叶基角的研究甚多, 但结论不一^[3-6]。本试验结果表明, 水稻上三叶在温光条件优越的汉源点趋于短、窄、厚、直, 虽然其 LAI 更大但更加紧凑的株叶形态有利于降低消光系数, 冠层结构更为合理。

研究还表明, 随氮肥后移程度的增加, 冠层透光率、叶片厚度及叶基角均随之增加, 但上三叶大小在温江点和汉源点分别趋于增加和减小, 扩大了水稻叶片在弱光下增大、强光下减小^[16]的趋势, 可能与温光条件改变后上三叶形成时期穗肥用量与内源激素或碳代谢酶的关系发生变化有关^[19-20]。同时, 研究发现, 随氮肥后移程度的增加叶基角虽然有所增大, 但抽穗后穗子成为影响群体光分布的重要因素^[21], k 值因结实期单位面积穗数的减少反而有所降低。

此外, 本试验结果也表明, 宽窄行栽培改等行距为宽窄行, 三角形栽培改行列分布为行间错穴, 且每穴 3 株按三角形分布, 均有利于提高上三叶大小、叶片厚度及冠层透光性能, 因而在群体数量较

表 3 两种生态条件下氮肥运筹和栽培方式对群体光合生产的影响

Table 3 Effects of nitrogen fertilizer regime and cultivation models on photosynthetic production under two kinds of ecological conditions

氮肥运筹方式 Nitrogen fertilizer regime	栽培方式 Cultivation model	抽穗期 Heading			抽穗后 15 d 15 d after heading			抽穗后 30 d 30 d after heading		
		CAP	CR	CR/TCAP (%)	CAP	CR	CR/TCAP (%)	CAP	CR	CR/TCAP (%)
四川温江 Wenjiang, Sichuan										
N1	A1	3.03bcd	1.78bc	36.98bc	2.31bc	1.78bc	43.44abc	1.18de	0.96bc	45.02bcd
	A2	3.50a	2.40a	40.52a	2.63a	1.99a	43.03abc	1.35ab	1.00ab	42.10de
	A3	2.63fg	1.53de	36.63bc	2.01def	1.53d	43.02abc	1.00fg	0.93cd	48.17a
	A4	2.78def	1.60cd	36.66bc	1.92efg	1.48de	43.56abc	1.17de	1.04a	47.03ab
	平均值 Average	2.98	1.83	37.70	2.22	1.69	43.26	1.18	0.98	45.52
N2	A1	3.12bc	1.53de	32.74e	1.98def	1.66c	45.57a	1.00fg	0.83ef	45.45abc
	A2	2.93cde	1.90b	39.33ab	2.20cd	1.83b	45.49ab	1.08ef	0.79f	42.28cd
	A3	3.27ab	1.40def	30.13f	2.58ab	1.53d	37.31e	1.48a	0.88de	37.78f
	A4	2.80def	1.50de	34.92cde	1.95defg	1.40ef	41.86bcd	1.28bcd	0.92cd	42.03de
	平均值 Average	3.03	1.58	34.28	2.18	1.60	42.56	1.21	0.85	41.89
N3	A1	2.49g	1.33ef	34.57cde	1.78fg	1.28gh	41.80cd	0.88gh	0.70g	44.03bcd
	A2	2.63fg	1.53de	35.97cd	1.69g	1.20h	41.58cd	0.83h	0.67g	44.22bcd
	A3	2.55fg	1.28f	33.31de	1.83fg	1.28gh	41.08cd	1.08ef	0.68g	38.92ef
	A4	2.76ef	1.33ef	32.90e	2.15cde	1.34fg	38.56de	1.33bc	0.82ef	38.25f
	平均值 Average	2.61	1.36	34.19	1.86	1.27	40.75	1.03	0.72	41.36
四川汉源 Hanyuan, Sichuan										
N1	A1	3.98bc	2.05b	34.57cd	2.65bc	1.98a	42.65b	1.28c	1.00abc	44.95ab
	A2	4.67a	2.38a	35.97bc	3.28a	2.01a	38.12cde	1.62a	1.02ab	38.55d
	A3	3.97bc	1.95bc	33.31d	2.37cde	1.79b	43.03b	1.08de	0.90cde	45.36ab
	A4	3.83cd	1.53d	32.90de	2.40cd	1.41d	37.14cde	1.07ef	0.98bc	47.72a
	平均值 Average	4.11	1.98	32.34	2.67	1.80	40.23	1.26	0.98	44.14
N2	A1	3.79cd	1.95bc	33.90b	2.44cd	1.66bc	40.49bc	1.27c	0.94bcd	42.63bc
	A2	3.29e	1.89bc	36.49a	2.17de	1.93a	47.02a	1.24c	0.95bcd	43.16b
	A3	4.16b	1.78c	30.04de	2.71b	1.58c	36.93de	1.40b	1.09a	43.83b
	A4	3.55de	1.46d	29.21de	2.36cde	1.18e	33.32fg	1.23c	0.96bcd	43.81b
	平均值 Average	3.70	1.77	32.41	2.42	1.59	39.44	1.29	0.99	43.40
N3	A1	3.45e	1.78c	34.10ab	2.34cde	1.38d	37.13cde	1.25c	0.83ef	40.08cd
	A2	3.29e	1.45d	30.54cde	2.06e	1.32d	39.02cd	1.18cde	0.76f	39.36d
	A3	3.40e	1.54d	31.27cd	2.43cd	1.32d	35.10ef	1.19cd	0.93bcde	43.72b
	A4	3.43e	1.11e	24.39f	2.28de	1.02f	30.98g	1.09de	0.88de	44.33b
	平均值 Average	3.39	1.47	30.07	2.28	1.26	35.56	1.18	0.85	41.87

A1: 宽窄行栽培; A2: 三角形栽培; A3: 扩行减株稀植栽培; A4: 抛秧栽培; N1: 底、蘖、穗肥比例为 6 : 3 : 1; N2: 底、蘖、穗肥比例为 5 : 2 : 3; N3: 底、蘖、穗肥比例为 4 : 1 : 5; CAP 和 CR 单位均为 $\text{g CO}_2 \text{ m}^{-2} \text{ h}^{-1}$ 。同一地点同列中不同字母表示在 0.05 水平差异显著。

A1: wide-narrow row spacing cultivation; A2: triangle cultivation; A3: spreading planting by expanding row spacing and reducing plant space; A4: Scattered Planting cultivation; N1: the ratio of nitrogen application at transplanting stage, tillering stage and booting stage was 6:3:1; N2: the ratio of nitrogen application at transplanting stage, tillering stage and booting stage was 5:2:3; N3: the ratio of nitrogen application at transplanting stage, tillering stage and booting stage was 4:1:5, units of CAP and CR both are $\text{g CO}_2 \text{ m}^{-2} \text{ h}^{-1}$. Data of same location in each column followed by different letters are significantly different at the 0.05 probability level.

大的情况下, 二者的冠层特性更有利于光合生产。抛秧栽培前期群体发展快、群体大^[22], 加之田间的无序分布, 导致其抽穗后遮蔽严重, 冠层通透性不及其他栽培方式^[15], 当穗肥比例增加时, 更有利于

改善其后期群体质量, 提高光能截获及光合生产能力。同时, 随生态条件的改善和氮肥后移程度的增加, 群体通透性提高, 植株田间分布对叶片大小、厚度造成的影响随之减弱。

表 4 两种生态条件下氮肥运筹和栽培方式对群体质量和产量的影响

Table 4 Effects of nitrogen fertilizer regime and cultivation models on population quality, panicles and grain yield under two kinds of ecological conditions

氮肥运筹方式 Nitrogen fertilizer regime	栽培方式 Cultivation model	抽穗期茎鞘重 SSWH (g)	高效叶面积率 RLAPT (%)	有效叶面积率 RLAF-3FL (%)	抽穗至成熟期干 物质积累量 DMAHM (t hm ⁻²)	有效穗数 EPN (×10 ⁴ hm ⁻²)	籽粒产量 GY (t hm ⁻²)
四川温江 Wenjiang, Sichuan							
N1	A1	2.63bc	65.03ef	86.08e	5.45d	200.53abc	9.93bc
	A2	2.46de	65.53e	87.44e	5.94bcd	197.93bc	10.53a
	A3	2.42e	63.83ef	82.14f	3.74e	199.83abc	8.97ef
	A4	2.37e	62.57f	80.27f	3.34e	213.07a	8.80f
	平均值 Average	2.47	64.24	83.98	4.62	202.84	9.56
N2	A1	2.72b	70.23d	91.57cd	5.21d	187.80cde	9.47cde
	A2	2.65bc	70.80cd	92.15bcd	5.59cd	180.60def	9.83bcd
	A3	2.75b	76.13a	93.47abc	6.70ab	189.30cd	10.27ab
	A4	2.58cd	71.17cd	90.69d	5.52cd	202.80ab	9.87bcd
	平均值 Average	2.69	72.08	91.97	5.75	190.13	9.86
N3	A1	2.85a	71.23cd	94.63a	5.19d	174.90ef	9.20e
	A2	2.69bc	71.03cd	94.20ab	5.49d	173.53f	9.30def
	A3	2.88a	73.40bc	94.53a	6.36abc	175.50ef	9.53cde
	A4	2.61bc	73.77bc	93.57abc	7.14a	193.20bcd	10.27ab
	平均值 Average	2.76	72.36	94.23	6.05	179.28	9.58
四川汉源 Hanyuan, Sichuan							
N1	A1	2.95de	66.93de	88.35d	8.91bc	232.20bcd	12.21cde
	A2	2.85ef	68.70d	90.04d	9.66b	248.53a	13.99a
	A3	2.75fg	64.73e	85.62e	8.67bc	236.50bc	12.15de
	A4	2.69g	64.07e	83.82e	8.19c	248.73a	12.04e
	平均值 Average	2.81	66.11	86.96	8.83	241.49	12.60
N2	A1	3.04abcd	73.83abc	92.84c	9.42b	226.50de	12.51bcde
	A2	2.94de	73.33bc	93.71bc	9.42b	220.10ef	12.71bcd
	A3	3.08abc	77.60a	95.37ab	10.87a	231.73bcd	13.02b
	A4	2.80f	76.77ab	92.74c	9.63b	240.17ab	12.75bc
	平均值 Average	2.97	75.38	93.67	9.86	229.63	12.75
N3	A1	3.13ab	73.37bc	93.04bc	9.56b	215.07f	12.05e
	A2	3.00cd	72.83c	94.24abc	8.89bc	196.77f	11.36f
	A3	3.15a	76.33abc	95.69ab	9.54b	216.07f	12.06e
	A4	3.03abcd	75.80abc	92.96c	9.48b	227.77de	12.34cde
	平均值 Average	3.08	74.58	93.98	9.37	213.92	11.95

A1: 宽窄行栽培; A2: 三角形栽培; A3: 扩行减株稀植栽培; A4: 抛秧栽培; N1: 底、蘖、穗肥比例为 6 : 3 : 1; N2: 底、蘖、穗肥比例为 5 : 2 : 3; N3: 底、蘖、穗肥比例为 4 : 1 : 5。同一地点同列中不同字母表示在 0.05 水平差异显著。

A1: wide-narrow row spacing cultivation; A2: triangle cultivation; A3: spreading planting by expanding row spacing and reducing plant space; A4: Scattered planting cultivation; N1: the ratio of nitrogen application at transplanting stage, tillering stage and booting stage was 6:3:1; N2: the ratio of nitrogen application at transplanting stage, tillering stage and booting stage was 5:2:3; N3: the ratio of nitrogen application at transplanting stage, tillering stage and booting stage was 4:1:5; SSWH: single stem and sheath weight in heading; RLAPT: ratio of leaf area of productive tillers (%); RLAF-3FL: ratio of leaf area from flag leaf to 3rd leaf from top of productive tillers; DMAHM: dry matter accumulation from heading to maturing stage; EPN: effective panicle number; GY: grain yield. Data of same location in each column followed by different letters are significantly different at the 0.05 probability level.

3.2 群体光合生产

群体光合速率能准确地描述每单位土地面积上的光合能力, 而且综合了基因型效应、叶片形态、

冠层结构等因素, 与作物产量具有密切的关系^[22]。本研究表明, 在温光条件较好的汉源点群体质量各项指标得到提高, 抽穗后更高的 CAP 和结实中前期

表 5 两种生态条件下氮肥运筹和栽培方式对抽穗后叶面积指数(LAI)和消光系数(k)的影响
Table 5 Effects of nitrogen fertilizer regime and cultivation models on LAI and light extinction coefficient under two kinds of ecological conditions

氮肥运筹方式 Nitrogen fertilizer regime	栽培方式 Cultivation model	四川温江 Wenjiang, Sichuan			四川汉源 Hanyuan, Sichuan		
		抽穗期 Heading	抽穗后 15 d 15AH	抽穗后 30 d 30AH	抽穗期 Heading	抽穗后 15 d 15AH	抽穗后 30 d 30AH
LAI							
N1	A1	7.37ab	6.86ab	3.94bcd	7.96ab	7.08b	4.51abcd
	A2	7.27b	6.80abc	4.05b	7.89ab	7.48a	4.64a
	A3	7.30b	6.84ab	3.85def	7.77bc	7.10b	4.19e
	A4	7.52a	7.01a	3.91cde	8.01a	7.23b	4.30de
	平均值 Average	7.37	6.88	3.94	7.91	7.22	4.41
N2	A1	6.89c	6.51de	3.82efg	7.53de	6.82c	4.42bcd
	A2	6.66d	6.43e	3.80efg	7.45de	7.11b	4.45abcd
	A3	6.75cd	6.59cd	4.03bc	7.60cd	7.11b	4.60ab
	A4	7.26b	6.71bcd	4.03bc	7.79bc	7.09b	4.48abcd
	平均值 Average	6.89	6.56	3.92	7.59	7.03	4.49
N3	A1	6.35e	6.14f	3.72g	7.16f	6.46d	4.38cde
	A2	6.15f	6.03f	3.73fg	6.98f	6.84c	4.48abcd
	A3	6.32ef	6.13f	3.88de	7.09f	6.78c	4.56abc
	A4	6.61d	6.42e	4.20a	7.37e	6.78c	4.53abc
	平均值 Average	6.36	6.18	3.88	7.15	6.72	4.49
消光系数 Light extinction coefficient (<i>k</i>)							
N1	A1	0.42de	0.42ef	0.63c	0.39c	0.43cd	0.57b
	A2	0.43cde	0.44cde	0.63c	0.40bc	0.42de	0.56b
	A3	0.45ab	0.46b	0.67b	0.43a	0.45ab	0.64a
	A4	0.46a	0.50a	0.75a	0.44a	0.46a	0.66a
	平均值 Average	0.44	0.46	0.67	0.42	0.44	0.61
N2	A1	0.41e	0.42ef	0.60d	0.39c	0.43cde	0.55bc
	A2	0.43cde	0.44def	0.62cd	0.40bc	0.41de	0.55bc
	A3	0.44bc	0.45bcd	0.62cd	0.41b	0.43cde	0.55bc
	A4	0.46ab	0.46b	0.66b	0.43a	0.44bc	0.57b
	平均值 Average	0.44	0.44	0.62	0.41	0.43	0.56
N3	A1	0.41e	0.42f	0.57e	0.39c	0.43cde	0.51d
	A2	0.43cde	0.43def	0.57e	0.40bc	0.41e	0.50d
	A3	0.43cd	0.43def	0.57e	0.41b	0.42cde	0.51cd
	A4	0.46ab	0.46b	0.60d	0.41b	0.44bc	0.55bc
	平均值 Average	0.43	0.44	0.58	0.41	0.42	0.52

A1: 宽窄行栽培; A2: 三角形栽培; A3: 扩行减株稀植栽培; A4: 抛秧栽培; N1: 底、蘖、穗肥比例为 6 : 3 : 1; N2: 底、蘖、穗肥比例为 5 : 2 : 3; N3: 底、蘖、穗肥比例为 4 : 1 : 5。同一地点同列中不同字母表示在 0.05 水平差异显著。

A1: wide-narrow row spacing cultivation; A2: triangle cultivation; A3: spreading planting by expanding row spacing and reducing plant space; A4: Scattered planting cultivation; N1: the ratio of nitrogen application at transplanting stage, tillering stage and booting stage was 6:3:1; N2: the ratio of nitrogen application at transplanting stage, tillering stage and booting stage was 5:2:3; N3: the ratio of nitrogen application at transplanting stage, tillering stage and booting stage was 4:1:5; 15AH: 15 d after heading, 30AH: 30 d after heading. Data of same location in each column followed by different letters are significantly different at the 0.05 probability level.

更低的 CR/TCAP 是其群体光合生产优势突出，抽穗后干物质生产能力更强，最终产量显著提高的主要原因。

氮素营养是人们调控作物光合生产率的重要手段之一^[23-25]，穗肥施用比例的增加不仅有利于提高水稻抽穗后剑叶光合性能^[26]，还有利于改善群体透

表 6 两种生态条件下氮肥运筹对不同栽培方式抽穗期叶片形态的影响

Table 6 Effects of nitrogen fertilizer regime and cultivation models on leaf morphological factor under two kinds of ecological conditions

地点 Location	氮肥运筹方式 Nitrogen fertilizer regime	栽培方式 Cultivation model	叶长 Leaf length (cm)			叶宽 Leaf width (cm)			叶基角 Leaf angle (°)			比叶重 Specific leaf weight (mg cm ⁻²)
			剑叶	倒二叶	倒三叶	剑叶	倒二叶	倒三叶	剑叶	倒二叶	倒三叶	
			1 st leaf from top	2 nd leaf from top	3 rd leaf from top	1 st leaf from top	2 nd leaf from top	3 rd leaf from top	1 st leaf from top	2 nd leaf from top	3 rd leaf from top	
四川温江 Wenjiang, Sichuan	N1	A1	42.50c	52.66bc	62.97d	2.27fg	2.02def	1.86d	15.67cde	20.80ab	24.00cd	4.16de
		A2	42.59c	52.04c	63.01d	2.32def	2.03cdef	1.87cd	13.50f	18.60c	23.80d	4.31c
		A3	42.66c	51.87c	60.54ef	2.29efg	2.01ef	1.86d	16.67abc	20.40b	24.25cd	3.94f
		A4	42.86c	49.42d	58.41g	2.23g	1.94f	1.79e	15.33de	20.65ab	26.17abc	4.04ef
		平均值 Average	42.65	51.50	61.23	2.28	2.00	1.84	15.29	20.11	24.55	4.11
	N2	A1	43.51abc	52.92bc	64.19abcd	2.36bcd	1.99ef	1.91abc	17.00ab	21.20ab	24.83bcd	4.40bc
		A2	43.87abc	52.31c	63.63cd	2.38abcd	2.18ab	1.91abc	15.00e	19.00c	24.00cd	4.47ab
		A3	43.28bc	52.17c	65.54a	2.35cd	2.07bcde	1.89bcd	17.00ab	20.60ab	24.50bcd	4.59a
		A4	43.92abc	49.79d	59.13fg	2.33d	2.00ef	1.86d	16.33bcd	20.80ab	24.40bcd	4.29cd
		平均值 Average	43.65	51.80	63.12	2.36	2.06	1.89	16.33	20.40	24.43	4.44
	N3	A1	43.94abc	53.89ab	64.71abc	2.41abc	2.03cdef	1.92a	17.67a	21.66a	26.67ab	4.57a
		A2	44.76ab	53.38abc	63.92bcd	2.43a	2.20a	1.95a	15.33de	20.83ab	24.87bcd	4.56a
		A3	44.82a	54.85a	65.38ab	2.42ab	2.15abc	1.90abcd	17.00ab	21.50ab	27.67a	4.59a
		A4	44.69ab	50.24d	61.29e	2.38abcd	2.13abcd	1.89bcd	17.50ab	21.34ab	27.33a	4.58a
		平均值 Average	44.55	53.09	63.83	2.41	2.13	1.92	16.87	21.33	26.63	4.58
四川汉源 Hanyuan, Sichuan	N1	A1	39.90a	48.69abc	53.14a	2.12a	1.90a	1.65a	15.33de	17.00ef	21.67de	4.54cd
		A2	39.57a	49.32a	52.88a	2.11a	1.88ab	1.66a	14.20f	16.25ef	20.75e	4.66abc
		A3	40.46a	49.45abc	49.96b	2.13a	1.82abc	1.64a	15.33de	17.01f	22.33bcde	4.34d
		A4	41.04a	49.10ab	50.41b	2.14a	1.82abc	1.67a	15.50cde	17.25g	24.00ab	4.33d
		平均值 Average	40.24	49.14	51.60	2.13	1.85	1.66	15.09	16.88	22.19	4.47
	N2	A1	40.28a	48.57abc	50.33b	2.13a	1.77cd	1.58b	16.00bcd	18.33c	23.00abcd	4.66abc
		A2	40.55a	47.39cd	50.07b	2.09a	1.74cd	1.55bc	14.60ef	16.67ef	22.25cde	4.70abc
		A3	40.52a	48.67abc	49.90b	2.10a	1.79bcd	1.58b	16.07bcd	17.33de	22.67abcd	4.68abc
		A4	40.11a	47.73bcd	48.82bc	2.09a	1.75cd	1.54bc	16.13bcd	17.67ef	23.42abc	4.65bc
		平均值 Average	40.37	48.09	49.78	2.10	1.76	1.57	15.70	17.50	22.84	4.67
	N3	A1	40.67a	47.66cd	49.83b	2.13a	1.75cd	1.56bc	17.00ab	21.00b	24.33a	4.83ab
		A2	41.17a	46.59d	49.27bc	2.11a	1.70d	1.55bc	15.33de	19.00c	23.00abcd	4.85ab
		A3	40.81a	47.14d	48.62bc	2.11a	1.76cd	1.54bc	17.60a	22.17a	23.75abc	4.88a
		A4	41.00a	47.02d	47.61c	2.11a	1.73cd	1.54c	16.50bc	20.50cd	23.83abc	4.87ab
		平均值 Average	40.91	47.10	48.83	2.12	1.74	1.55	16.61	20.67	23.73	4.86

A1: 宽窄行栽培; A2: 三角形栽培; A3: 稀植栽培; A4: 抛秧栽培; N1: 底、蘖、穗肥比例为6:3:1; N2: 底、蘖、穗肥比例为5:2:3; N3: 底、蘖、穗肥比例为4:1:5。同一地点同列中不同字母表示在0.05水平差异显著。

A1: wide-narrow row spacing cultivation; A2: triangle cultivation; A3: spreading planting by expanding row spacing and reducing plant space; A4: Scattered Planting cultivation; N1: the ratio of nitrogen application at transplanting stage, tillering stage and booting stage was 6:3:1; N2: the ratio of nitrogen application at transplanting stage, tillering stage and booting stage was 5:2:3; N3: the ratio of nitrogen application at transplanting stage, tillering stage and booting stage was 4:1:5. Data of same location in each column followed by different letters are significantly different at the 0.05 probability level.

光条件、增强下位叶光合潜力^[27], 而本试验的研究表明, 穗肥施用比例的增加虽然提高了抽穗期茎鞘干重、高效叶面积率和有效叶面积率等群体质量指标, 但也降低了抽穗后 LAI, 群体光能截获能力随之减弱, 最终两地 CR/TCAP 均呈降低趋势, CAP 在温江点和汉源点分别以氮肥运筹比例为 5:2:3 和 6:3:1 时最高, 这说明利用氮肥管理措施提高 CAP 应立足于一定群体基础上植株个体光合性能的改善, 而 CR/TCAP 的降低有赖于高效叶面积率的增加。

作物高产群体要求提高群体光合速率以制造更多的光合产物, 并且降低呼吸消耗, 使更多的光合产物用于干物质积累, 从而提高光能利用率^[28], 在本试验条件下, 不同氮肥运筹下 CAP 的提高和 CR 的减少往往并不同步, 高 CAP 并非意味着抽穗后干物质积累量乃至产量的提高, 这跟前人对 CAP 和抽穗后物质积累量关系的研究结论^[8]并不一致。CR/TCAP 将光合生产和暗呼吸消耗联系起来, 体现了光合产物向物质积累分配的效率高低, 最终用于物质积累的光合产物不仅取决于 CAP, 还与 CR/TCAP 的高低有关。就不同生态条件而言, 在温江点当氮肥运筹比例为 4:1:5 时, 干物质积累量的提高主要原因在于 CR/TCAP 的降低, 而在温光资源更为丰富的汉源点, 当氮肥运筹比例为 5:3:2 时, 光合生产能力的提高关键在于 CAP 有所降低而 CR/TCAP 显著减小。从栽培方式看, 不同栽培方式在不同的氮肥运筹方式下实现其物质生产优势具有多样性。当氮肥运筹比例为 6:3:1 时, 宽窄行和三角形栽培 CAP 提高的同时结实中后期 CR/TCAP 增幅减小, 抽穗后群体光合生产能力因而得以提高; 当氮肥运筹比例为 5:2:3 时, 扩行减株稀植栽培 CAP 升高的同时 CR/TCAP 并未增加甚至有所减小, 抽穗后群体光合生产能力因而高于其他栽培方式; 当氮肥运筹比例为 4:1:5 时, 抛秧栽培在温江点结实中后期 CAP 显著提高的同时 CR/TCAP 降低, 抽穗后群体光合生产优势明显, 但温光条件改善后该优势并无体现。

4 结论

水稻 CAP 的提高源于一定群体基础上植株个体光合性能的改善, 而 CR/TCAP 的降低则有赖于高效叶面积的增加。抽穗后群体光合生产能力高低不仅取决于 CAP, 还与 CR/TCAP 的高低有关, 因而提高抽穗后光合生产能力的途径具有多样性, 应根据当

地生态条件针对不同栽培方式选择适宜的氮肥管理措施。不同栽培方式间植株田间分布不同, 冠层特性发生改变, 抽穗期群体质量随之表现不一, 群体光合特性各有特点, 因此实现各栽培方式抽穗后群体光合生产优势的最佳氮肥运筹比例并不一致, 在本试验条件下宽窄行栽培和三角形栽培为 6:3:1, 扩行减株稀植栽培为 5:2:3, 而抛秧栽培在温江点和汉源点分别为 4:1:5 和 5:2:3。

References

- [1] Venkateswarlu B, Visperas R M. Source-sink relationships in crop plants. *Int Rice Res Paper Ser*, 1987, 125: 1-19
- [2] Ling Q-H(凌启鸿). Crop Population Quality (作物群体质量). Shanghai: Shanghai Scientific and Technical Publishers, 2000. pp 42-210 (in Chinese)
- [3] Zhou K-D(周开达), Ma Y-Q(马玉清), Liu T-Q(刘太清), Shen M-S(沈茂松). The breeding of subspecific heavy ear hybrid rice-exploration about super-high yield breeding of hybrid rice. *J Sichuan Agric Univ* (四川农业大学学报), 1995, 13(4): 403-407 (in Chinese with English abstract)
- [4] Yuan L-P(袁隆平). Hybrid rice breeding for super high yield. *Hybrid Rice* (杂交水稻), 1997, 12(6): 1-3 (in Chinese with English abstract)
- [5] Yang J-C(杨建昌), Zhu Q-S(朱庆森), Cao X-Z(曹显祖). Studies on the role of the mass canopy structure and photosynthetic characteristics in yield formation of rice. *Sci Agric Sin* (中国农业科学), 1992, 25(4): 7-14 (in Chinese with English abstract)
- [6] Ma J(马均), Ma W-B(马文波), Ming D-F(明东风), Yang S-M(杨世民), Zhu Q-S(朱庆森). Studies on the characteristics of rice plant with heavy panicle. *Sci Agric Sin* (中国农业科学), 2006, 39(4): 679-685 (in Chinese with English abstract)
- [7] Liu J-F(刘建丰), Yuan L-P(袁隆平), Deng Q-Y(邓启云), Chen L-Y(陈立云), Cai Y-D(蔡义东). A study on characteristics of photosynthesis in super high-yielding hybrid rice. *Sci Agric Sin* (中国农业科学), 2005, 38(2): 258-264 (in Chinese with English abstract)
- [8] Zhao Q-Z(赵全志), Huang P-S(黄丕生), Ling Q-H(凌启鸿). Relations between canopy apparent photosynthesis and store matter in stem and sheath between and yield and nitrogen regulations in rice. *Sci Agric Sin* (中国农业科学), 2001, 34(3): 304-310 (in Chinese with English abstract)
- [9] Chen D-C(陈德春), Yang W-Y(杨文钰), Ren W-J(任万军). Effects of rice seedlings horizontal distribution on the dynamics of rice population, canopy light transmittance rate and panicle characteristics. *Chin J Appl Ecol* (应用生态学报), 2007, 18(2): 359-365 (in Chinese with English abstract)
- [10] Wang J-L(王建林), Xu Z-J(徐正进), Yi X-Z(衣先众). Effects of seedling quantity and row spacing on yields and yield components of hybrid and conventional rice in northern China. *Chin J Rice Sci* (中国水稻科学), 2006, 20(6): 631-637 (in Chinese with English abstract)

English abstract)

- [11] Wang R-Q(汪仁全), Ma J(马均), Tong P(童平), Fu T-L(傅泰露), Li Y(李艳), Wu H-Z(吴和洲), Liu Z-B(刘志彬). Effects of planting method of triangle of system of rice intensification (TSRI) on photosynthetic characteristics and formation of grain yield. *Hybrid Rice* (杂交水稻), 2006, 21(6): 60–65 (in Chinese with English abstract)
- [12] Xie L-Y(谢立勇), Feng Y-X(冯永祥), Xu Z-J(徐正进). Effect of field arrangement on physiological characteristics of different panicle type rice. *J Shenyang Agric Univ* (沈阳农业大学学报), 2003, 34(6): 406–409 (in Chinese with English abstract)
- [13] Zhang Q(张强), Wan L-J(万靛军), Dai Q-G(戴其根), Huo Z-Y(霍中洋), Xu K(许轲), Zhang H-C(张洪程). A review of the nitrogen on biological characteristics and its high produce management in rice. *Reclaiming & Rice Cultivation* (垦殖与稻作), 2004, (5): 41–43 (in Chinese with English abstract)
- [14] Li G-H(李刚华), Zhang G-F(张国发), Chen G-L(陈功磊), Wang S-H(王绍华), Ling Q-H(凌启鸿), Ding Y-F(丁艳锋). Population characteristics of super japonica rice Ningjing 1 and Ningjing 3 and its responses to nitrogen. *Acta Agron Sin* (作物学报), 2009, 35(6): 1106–1114 (in Chinese with English abstract)
- [15] Lü C-G(吕川根), Hu N(胡凝), Yao K-M(姚克敏), Xia S-J(夏士健), Qi Q-M(漆庆明). Plant type and its effects on canopy structure at heading stage in various ecological areas for a two-line hybrid rice combination, Liangyoupeijiu. *Chin J Rice Sci* (中国水稻科学), 2009, 23(5): 529–536 (in Chinese with English abstract)
- [16] Tong P(童平), Yang S-M(杨世民), Ma J(马均), Wu H-Z(吴和洲), Fu T-L(傅泰露), Li M(李敏), Wang M-T(王明田). Photosynthetic characteristics and dry matter accumulation of hybrid rice varieties under different light conditions. *Chin J Appl Ecol* (应用生态学报), 2008, 19(3): 505–511 (in Chinese with English abstract)
- [17] Dong S-T(董树亭), Gao R-Q(高荣岐), Hu C-H(胡昌浩), Wang Q-Y(王群瑛), Wang K-J(王空军). Study of canopy photosynthesis property and high yield potential after anthesis in maize. *Acta Agron Sin* (作物学报), 1997, 23(3): 318–325 (in Chinese with English abstract)
- [18] Zou J-S(邹江石), Yao K-M(姚克敏), Lü C-G(吕川根), Hu X-Q(胡雪琼). Study on individual plant type character of Liangyoupeijiu rice. *Acta Agron Sin* (作物学报), 2003, 29(5): 652–657 (in Chinese with English abstract)
- [19] Seneweera S P, Basra A S, Barlow E W. Diurnal regulation of leaf blade elongation in rice by CO₂: Is it related to sucrose phosphate synthase activity. *Plant Physiol*, 1995, 108: 1471–1477
- [20] Shi X-D(时向东), Liu Y-F(刘艳芳), Wen Z-Q(文志强), Cheng G(程刚), Huang K-J(黄克久), Wu C-K(吴纯奎). Effects of nitrogen levels on growth and content of endogenous hormones of cigar wrapper leaves. *Acta Bot Boreali-occident Sin* (西北植物学报), 2007, 27(8): 1625–1630 (in Chinese with English abstract)
- [21] Wang J-L(王建林), Xu Z-J(徐正进). Effects of panicle type and row spacing on light distribution of rice canopy. *Chin J Rice Sci* (中国水稻科学), 2005, 19(5): 422–426 (in Chinese with English abstract)
- [22] Zhang H-C(张洪程), Dai Q-G(戴其根), Huo Z-Y(霍中洋), Xu K(许轲), Wei H-Y(魏海燕). Cultivation technical system of rice seedling broadcasting and its characteristics. *Sci Agric Sin* (中国农业科学), 2008, 41(1): 43–52 (in Chinese with English abstract)
- [23] Du M-W(杜明伟), Feng G-Y(冯国艺), Yao Y-D(姚炎帝), Luo H-H(罗宏海), Zhang Y-L(张亚黎), Xia D-L(夏东利), Zhang W-F(张旺锋). Canopy characteristics and its correlation with photosynthesis of super high-yielding hybrid cotton Biaozha AI and Shiza 2. *Acta Agron Sin* (作物学报), 2009, 35(6): 1068–1077 (in Chinese with English abstract)
- [24] Xiao K(肖凯), Zhang R-X(张荣铨), Qian W-P(钱维朴). The effect and regulating mechanism of nitrogen nutrition on canopy photosynthetic carbon assimilation in wheat. *Plant Nutr Fert Sci* (植物营养与肥料学报), 1999, 5(3): 235–243 (in Chinese with English abstract)
- [25] Jiang D(姜东), Yu Z-W(于振文), Su B(苏波), Xu Y-M(许玉敏), Yu S-L(余松烈). Effect of different application stage of nitrogen on root senescence in winters wheat. *Acta Agron Sin* (作物学报), 1997, 23(2): 180–190 (in Chinese with English abstract)
- [26] He P(何萍), Jin J-Y(金继运). Effect of N application rates on leaf senescence and its mechanism in spring maize. *Sci Agric Sin* (中国农业科学), 1998, 31(3): 66–71 (in Chinese with English abstract)
- [27] Chen H-Z(陈惠哲), Zhu D-F(朱德峰), Lin X-Q(林贤青), Zhang Y-P(张玉屏), Zhang W-X(张卫星). Effect of nitrogen application for spikelet promotion on growth and photosynthetic rate of canopy leaves in super hybrid rice. *J Hunan Agric Univ* (Nat Sci)(湖南农业大学学报·自然科学版), 2007, 33(5): 617–621 (in Chinese with English abstract)
- [28] Zhang J-X(张建新). Distribution of leaf photosynthetic capacity in canopy and its effect on canopy photosynthesis. *Acta Phyto-physiol Sin* (植物生理学报), 1988, 14(1): 1–8 (in Chinese with English abstract)
- [29] Yang J-S(杨吉顺), Gao H-Y(高辉远), Liu P(刘鹏), Li G(李耕), Dong S-T(董树亭), Zhang J-W(张吉旺), Wang J-F(王敬锋). Effects of planting density and row spacing form on the performances of canopy apparent photosynthesis of high-yield summer corn. *Acta Agron Sin* (作物学报), 2010, 36(7): 1226–1233 (in Chinese with English abstract)