

# 氮肥后移对抽穗后水分胁迫下冬小麦 光合特性及产量的影响\*

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**摘要** 采用子母桶栽土培法模拟冬小麦抽穗后不同的水分胁迫状态,研究了氮肥后移对冬小麦光合特性及产量的影响.设置3个氮肥处理,分别为 $N_1$ (基肥:拔节肥:开花肥=10:0:0)、 $N_2$ (6:4:0)和 $N_3$ (4:3:3),模拟冬小麦抽穗后2种水分胁迫(渍水胁迫、干旱胁迫),设正常供水为对照.结果表明:相同供水条件下, $N_2$ 和 $N_3$ 处理较 $N_1$ 处理显著提高冬小麦灌浆期旗叶的SPAD和光合速率,确保了收获时较高的穗数、穗粒数和地上部分生物量;氮肥后移处理显著提高了冬小麦的耗水量,但其籽粒产量和水分利用效率也显著提高.相同氮肥条件下,干旱胁迫和渍水胁迫处理较正常供水显著降低了冬小麦开花期和灌浆期旗叶的光合速率、千粒重、穗粒数和产量.与正常供水相比,各氮肥条件下干旱胁迫和渍水胁迫处理花后旗叶光合速率及籽粒产量的减小幅度均表现为 $N_1 > N_2 > N_3$ .表明氮肥后移通过提高旗叶SPAD、减缓花后旗叶光合速率的下降幅度、增加地上部分干物质积累量,调控产量及其构成要素,以减轻逆境灾害(干旱和渍水胁迫)对产量的影响.

**关键词** 氮肥后移; 冬小麦; 水分胁迫; 光合; 产量调控

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**Effects of postponing nitrogen application on photosynthetic characteristics and grain yield of winter wheat subjected to water stress after heading stage.** YANG Ming-da<sup>1,2</sup>, MA Shou-chen<sup>3</sup>, YANG Shen-jiao<sup>4</sup>, ZHANG Su-yu<sup>2</sup>, GUAN Xiao-kang<sup>2</sup>, LI Xue-mei<sup>1</sup>, WANG Tong-chao<sup>2</sup>, LI Chun-xi<sup>1</sup> (<sup>1</sup>College of Life Sciences, Henan Normal University, Xinxiang 453007, Henan, China; <sup>2</sup>College of Agronomy, Henan Agricultural University/Collaborative Innovation Center of Henan Grain Crops, Zhengzhou 450002, China; <sup>3</sup>School of Surveying and Land Information Engineering, Henan Polytechnic University, Jiaozuo 454000, Henan, China; <sup>4</sup>Farmland Irrigation Research Institute, Chinese Academy of Agricultural Sciences, Xinxiang 453003, Henan, China). -Chin. J. Appl. Ecol., 2015, 26(11): 3315-3321.

**Abstract:** A pot culture experiment was conducted to study the effects of postponing nitrogen (N) application on photosynthetic characteristics and grain yield of winter wheat subjected to water stress after heading stage. Equal in the total N rate in winter wheat growth season, N application was split before sowing, and/or at jointing and /or at anthesis at the ratio of 10:0:0 ( $N_1$ ), 6:4:0 ( $N_2$ ) and 4:3:3 ( $N_3$ ), combined with unfavorable water condition (either waterlogged or drought) with the sufficient water condition as control. The results showed that, under each of the water condition, both  $N_2$  and  $N_3$  treatments significantly improved the leaf photosynthetic rate and the SPAD value of flag leaf compared with  $N_1$  treatment during grain filling stage, and also the crop ear number, grain number per spike and above-ground biomass were increased. Although postponing nitrogen application increased water consumption, both grain yield and water use efficiency were increased. Compared with sufficient water supply, drought stress and waterlogging stress significantly reduced the photosynthetic rate of flag leaves at anthesis and grain filling stages, ear number, 1000-grain mass and yield under all of the N application patterns. The decline of photosynthetic rate under either

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drought stress or waterlogging stress was much less in  $N_2$  and  $N_3$  than in  $N_1$  treatments, just the same as the grain yield. The results indicated that postponing nitrogen application could regulate winter wheat yield as well as its components to alleviate the damages caused by unfavorable water stress by increasing flag leaf SPAD and maintaining flag leaf photosynthetic rate after anthesis, and promoting above-ground dry matter accumulation.

**Key words:** nitrogen postponing application; winter wheat; water stress; photosynthesis; yield regulation.

中国是世界上干旱和洪涝灾害频繁而严重的国家之一,并且随着全球气候变化及极端天气的频现,干旱、涝渍等气象灾害的发生频率有显著加剧的趋势<sup>[1-3]</sup>.水分胁迫是影响农业生产最主要的环境胁迫因素,在所有气象灾害中,干旱灾害和洪涝灾害对我国农业生产和经济造成损失最为严重,二者所占的比重达 70%~85%<sup>[4-5]</sup>.我国南方麦区雨量丰沛,在小麦生育中后期经常出现因多次或连续降雨而导致地下水位过高,一旦土壤排水不良就会对作物造成涝渍胁迫<sup>[6]</sup>,严重影响小麦的产量和品质<sup>[7-9]</sup>;而在我国北方麦区,特别是黄淮海农作区,常年降雨量少且分布不均,全年降水的 60%~80%集中在玉米生长季,小麦生长季(10 月—翌年 6 月)的降雨量一般 <300 mm,远不能满足小麦的正常生长,干旱是生产的主要矛盾<sup>[3,10]</sup>.生育后期干旱和渍水是限制我国小麦高产优质的主要因子<sup>[8-9,11]</sup>.

小麦在遭受渍水胁迫时,土壤缺氧致使地下部植株根系有氧呼吸受到抑制,根系活力降低,影响根系吸收及营养元素转运<sup>[3,12]</sup>,同时地上部植株正常生长发育受阻,库源器官生长发育受限<sup>[3]</sup>,叶片光合性能和叶绿素含量显著下降<sup>[13]</sup>,植株衰老进程加快,影响植株干物质的积累与分配<sup>[14]</sup>,最终导致产量降低与品质下降<sup>[7,15-16]</sup>.干旱胁迫主要降低小麦的光合速率,造成植株早衰,降低干物质积累量,并减弱干物质由源到汇的转运能力<sup>[17]</sup>,降低籽粒灌浆速率<sup>[11]</sup>,最终影响其产量<sup>[8,14]</sup>.合理运筹氮肥是改善作物光合特性,提高产量的重要调控措施.前氮后移对冬小麦的生长及产量有显著的调控作用,可以提高旗叶的光合速率及延长高值持续时间<sup>[18]</sup>,还可以提高营养器官的氮素转运量和花后氮素同化量及籽粒蛋白质含量,最终提高冬小麦产量、品质及氮素吸收利用效率<sup>[11,19-20]</sup>,该技术已广泛应用于农业生产中.但当冬小麦生育后期遭遇洪涝或干旱等气象灾害时,前氮后移施肥技术对冬小麦生长及产量的调控作用如何,能否缓解渍害和旱灾对产量造成的不利影响,前人对此研究较少.武文明等<sup>[21]</sup>研究认为,孕穗期遭受短暂(7 d)的渍水胁迫,氮肥后移的

补偿效应优于氮肥全部基施,能显著减轻渍水逆境对光合器官的破坏并改善旗叶光合性能.范雪梅等<sup>[22]</sup>研究认为,在花后持续干旱(50%田间持水率)情况下,增施氮肥可以提高旗叶的光合速率及 SPAD 值,并能提高叶片及籽粒的可溶性糖含量.目前,有关氮肥后移对冬小麦生育后期持续水分胁迫的调控效应的研究较少.为此,本研究通过模拟生育后期较长时间段的水分胁迫来探讨氮肥后移对冬小麦遭受逆境灾害的调控效应,以为农业生产中冬小麦的抗逆稳产栽培提供科学依据.

## 1 材料与方法

### 1.1 供试材料与试验设计

以河南省大面积推广种植的“百农矮抗 58”为试验材料,于 2012 年 10 月—2013 年 5 月在河南师范大学(34°35' N, 115°34' E)植物学网室简易遮雨棚下进行.采用桶栽土培法,桶为圆柱形,分为母桶和子桶,母桶内径 31 cm,高 38 cm,埋入土中,桶檐高出地面 5 cm,子桶内径 30 cm,高 38 cm.子桶底部铺有约 5 cm 厚的砂粒过滤层用于调节下层土壤的水分及空气状况.试验土壤取自河南师范大学小麦试验田 0~30 cm 耕层土,土壤类型为中壤土,田间持水量(FWC)为 24.0%,土壤容重  $1.25 \text{ g} \cdot \text{cm}^{-3}$ ,有机质  $9.32 \text{ g} \cdot \text{kg}^{-1}$ ,全氮  $0.26 \text{ g} \cdot \text{kg}^{-1}$ ,全磷  $1.35 \text{ g} \cdot \text{kg}^{-1}$ ,速效氮  $30.25 \text{ g} \cdot \text{kg}^{-1}$ ,速效磷  $15.56 \text{ mg} \cdot \text{kg}^{-1}$ ,速效钾  $120 \text{ mg} \cdot \text{kg}^{-1}$ .装土前将土壤风干碾碎并过筛,分层装入子桶,并镇压达到土壤容重.为防止土壤表面水分蒸发过快和土壤板结,在桶中部放置直径 3 cm 的 PVC 管用于供水.插入土壤部分的 PVC 管周围有小孔,并用尼龙网缠好,防止灌水过程中土壤颗粒堵塞 PVC 管.

采用双因素完全随机区组设计,设 3 种施氮方式,生育期内总施氮量相同,以氮肥基追比(基施氮量和追施氮量的比例)10:0:0,记为  $N_1$ ;N 肥基追比 6:4:0 和 4:3:3,分别记作  $N_2$  和  $N_3$ ,拔节期和开花期追施氮肥.设置 3 种供水水平,生育前期(抽穗期前)正常供水(土壤含水率为 70%~75%

FWC), 抽穗期后模拟不同的水分胁迫: 渍水胁迫 (始终使桶内土面处于明水状态, 补水周期 2~3 d); 干旱胁迫 (45%~50% FWC); 并设置对照 (正常供水, 70%~75% FWC). 共有 3×3=9 个处理组合, 每处理重复 4 次, 共 36 桶. 全生育期施纯 N 240 kg·hm<sup>-2</sup>、P<sub>2</sub>O<sub>5</sub> 100 kg·hm<sup>-2</sup>、K<sub>2</sub>O 112.5 kg·hm<sup>-2</sup>; N 肥基施部分和 P、K 肥制成水溶液, 在播种前分桶浇施土中; 拔节期和开花期追施 N 肥处理, 追施部分以尿素水溶液浇施.

2012 年 10 月 17 日播种, 三叶期每桶留基本苗 30 株. 采用称量法控制土壤水分, 当各桶土壤水分低于设计标准时用量筒加水, 记录各桶每次加水量, 由水量平衡方程计算各生育时期总的耗水量. 由于渍水胁迫处理在抽穗期后要始终保持明水状态, 因此不计算总的加水量和总耗水量. 2013 年 5 月 28 日收获.

1.2 测定项目与方法

1.2.1 叶绿素值 (SPAD) 2013 年 5 月 14 日 (灌浆期) 用日产 SPAD—502 测定旗叶的 SPAD 值.

1.2.2 光合速率 分别在 2013 年 4 月 24 日 (开花期) 和 5 月 14 日 (灌浆期) 上午 9:00—11:00, 使用 Li-6400 光合测定系统测定各处理小麦旗叶的光合速率. 每处理取 4 株小麦进行测定, 取平均值.

1.2.3 地上部分生物量 成熟期, 将每桶所有植株全部连根拔出, 洗净根茎上的泥土, 剪掉根系, 放置于烘箱中 105 ℃ 杀青 0.5 h, 80 ℃ 恒温烘干至恒量, 用电子天平称干物质量.

1.2.4 产量及其构成要素 成熟期, 统计每桶小麦有效穗数. 每桶选取 20 个麦穗, 烘干脱粒后测定穗粒数 (先测地上部分生物量后考种), 最后全部脱粒测定籽粒产量.

1.3 数据处理

水分利用效率 (WUE, kg·m<sup>-3</sup>) = 每桶的籽粒产量/耗水量. 其中, 耗水量为播种与收获时土壤水分的差值加上生育期的灌水量.

采用 Excel 软件作图, 并用 SAS 8.0 软件对数据进行统计分析, 首先对不同处理间的指标进行方差分析, 若差异显著, 再进行 LSD 多重比较 (α=0.05).

2 结果与分析

2.1 冬小麦的叶绿素含量

由图 1 可以看出, 与 N<sub>1</sub> (氮肥全部基施) 处理相比, N<sub>2</sub> (氮肥基追比 6:4:0) 和 N<sub>3</sub> (氮肥基追比 4:3:3) 处理均显著提高了冬小麦灌浆期旗叶的

叶绿素含量; 在正常供水、渍水胁迫和干旱胁迫条件下分别显著提高 21.4% 和 21.5%、35.5% 和 35.4%、27.4% 和 27.5%. 相同氮肥处理下, 与正常供水相比, 小麦灌浆期渍水和干旱逆境均导致旗叶叶绿素含量显著降低; 其减小幅度在 2 种氮肥后移处理中差别不大, 均小于氮肥全部基施处理, 氮肥后移处理冬小麦表现出对生育后期水分胁迫的缓解效应.

2.2 冬小麦的光合速率

由图 2 可以看出, 冬小麦开花期和灌浆期的干

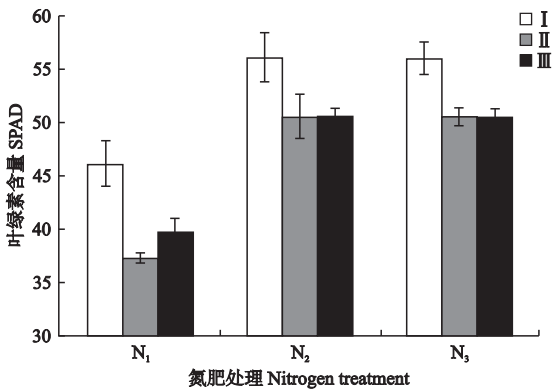


图 1 不同处理条件下冬小麦灌浆期旗叶的 SPAD  
Fig.1 Flag leaf SPAD of winter wheat at filling stage under different treatments.

I: 正常供水 Sufficient water supply; II: 渍水胁迫 Waterlogging stress; III: 干旱胁迫 Drought stress. 下同 The same below.

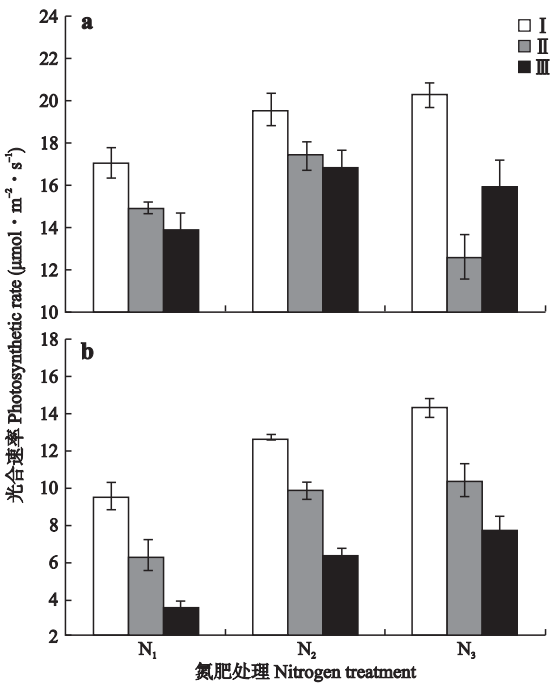


图 2 不同处理条件下开花期 (a) 和灌浆期 (b) 冬小麦的光合速率  
Fig.2 Photosynthetic rate of flag leaf of winter wheat at anthesis stage (a) and filling stage (b) under different treatments.

旱胁迫和渍水胁迫均显著降低小麦旗叶的净光合速率。开花期,在正常供水和干旱胁迫下,氮肥后移处理( $N_2$ 和 $N_3$ )小麦旗叶的净光合速率显著高于 $N_1$ 处理,而2个氮肥后移处理间差别不大;渍水胁迫下,各氮肥处理小麦旗叶光合速率差异显著, $N_2>N_1>N_3$ 。灌浆期,各水分条件下小麦旗叶光合速率的变化趋势一致,均随着追氮比例的增大而增大;与正常供水相比, $N_1$ 、 $N_2$ 和 $N_3$ 处理下渍水胁迫及干旱胁迫旗叶净光合速率分别显著降低33.9%、21.7%、27.2%及62.9%、50.2%、45.9%,2个氮肥后移处理明显缓解了小麦生育后期水分逆境对旗叶光合能力的影响。 $N_1$ 、 $N_2$ 和 $N_3$ 处理冬小麦灌浆期旗叶净光合速率比开花期平均降低了59.0%、47.2%和33.0%。

2.3 冬小麦的产量性状

由表1可以看出,氮肥和水分处理均对冬小麦的产量、地上部分生物量及穗粒数有显著影响,氮肥还对冬小麦的穗数有显著影响,水分对冬小麦千粒重也有显著影响,水氮互作对冬小麦产量和千粒重影响显著。

相同水分条件下, $N_2$ 和 $N_3$ 处理冬小麦的产量、穗粒数和穗数均显著高于 $N_1$ 处理;各氮肥处理地上部分生物量表现为 $N_3>N_2>N_1$ ;但各氮肥处理间千粒重的差异不显著。相同氮肥处理下,不同水分处理冬小麦的产量均表现为正常供水>渍水胁迫>干旱胁迫。在 $N_1$ 、 $N_2$ 和 $N_3$ 处理下,与正常供水相比,渍水

胁迫和干旱胁迫处理冬小麦产量分别显著降低12.1%、9.8%、6.2%及31.9%、14.7%、12.9%。氮肥后移处理一定程度上减缓了水分胁迫下冬小麦产量的下降幅度。相同氮肥处理下,正常供水和渍水胁迫处理地上部分生物量均显著高于干旱胁迫处理。 $N_1$ 处理下,渍水胁迫和干旱胁迫处理穗粒数显著低于正常供水; $N_2$ 和 $N_3$ 处理下,渍水胁迫处理穗粒数均显著低于正常供水,但干旱胁迫和正常供水处理间差异不显著。相同氮肥处理下,渍水胁迫和干旱胁迫处理千粒重均显著低于正常供水。

2.4 冬小麦的耗水量及水分利用效率

由表2可以看出,氮肥和水分对冬小麦的耗水量有显著影响,氮肥还对冬小麦的水分利用效率有显著影响,水氮互作对冬小麦的水分利用效率有显著影响。

相同水分条件下,各氮肥处理耗水量和水分利用效率均表现为 $N_3>N_2>N_1$ ,各氮肥处理间耗水量的差异均达到显著水平。 $N_3$ 处理冬小麦的水分利用效率显著高于 $N_1$ 处理, $N_2$ 和 $N_3$ 处理间差异不显著。在 $N_1$ 、 $N_2$ 和 $N_3$ 处理下,干旱胁迫处理耗水量比正常供水分别显著下降28.2%、16.6%和14.6%。 $N_1$ 、 $N_2$ 和 $N_3$ 处理下,干旱胁迫处理水分利用效率较正常供水分别降低16.1%、4.8%和2.3%,其中, $N_1$ 处理下各水分处理间差异达到显著水平, $N_2$ 和 $N_3$ 处理下各水分处理间的差异不显著。

表1 不同处理条件下冬小麦的产量及其性状  
Table 1 Yield and yield components of winter wheat under different treatments

处理 Treatment		穗数 Spike number	穗粒数 Grain number per spike	千粒重 1000-grain mass (g)	产量 Yield (g·pot <sup>-1</sup> )	地上部分生物量 Above-ground biomass (g·pot <sup>-1</sup> )
$N_1$	正常供水 Sufficient water supply	36.30±1.24c	24.70±3.22cd	47.10±1.90a	42.30±3.19e	116.70±4.78cd
	渍水胁迫 Waterlogging stress	38.51±0.47c	20.80±1.66e	42.52±1.28c	37.20±2.09f	116.60±3.09cd
	干旱胁迫 Drought stress	35.33±2.36c	18.30±1.48e	44.43±1.60bc	28.80±2.73g	99.30±6.85f
$N_2$	正常供水 Sufficient water supply	41.50±1.83b	27.90±2.12bc	45.92±3.22ab	50.00±2.45c	120.50±7.33c
	渍水胁迫 Waterlogging stress	45.52±3.34ab	21.40±2.24de	42.30±1.19c	45.13±0.92d	130.32±7.59b
	干旱胁迫 Drought stress	41.00±1.70b	26.33±1.50c	42.72±0.67c	43.60±2.29d	111.30±2.05de
$N_3$	正常供水 Sufficient water supply	44.00±3.69ab	32.40±2.04a	46.60±1.85a	59.31±1.91a	129.50±6.03b
	渍水胁迫 Waterlogging stress	47.52±3.31a	26.11±2.30c	42.72±2.65c	55.66±0.70b	135.00±7.07a
	干旱胁迫 Drought stress	44.00±2.89ab	30.32±2.90ab	42.22±1.88c	51.62±2.23c	117.27±4.92cd
F 值	氮肥 Nitrogen	72.00 **	33.02 **	1.82	230.13 **	37.58 **
F value	水分 Water	7.39	15.05 **	6.61 **	51.90 **	46.16 **
	氮肥×水分 Nitrogen × Water	5.54 **	2.77	2.96 *	4.80 **	0.43

同列不同小写字母表示不同处理间差异显著 ( $P<0.05$ ) Different small letters in the same column meant significant difference among different treatments at 0.05 level. \*  $P<0.05$ ; \*\*  $P<0.01$ . 下同 The same below.

表 2 不同处理下冬小麦耗水量和水分利用效率  
Table 2 Water consumption and water use efficiency of winter wheat under different treatments

处理 Treatment		耗水量 Water consumption (mm)	水分利用效率 Water use efficiency (kg · m <sup>-3</sup> )
N <sub>1</sub>	正常供水 Sufficient water supply	299.22±3.26d	1.55±0.06b
	干旱胁迫 Drought stress	214.58±5.78e	1.30±0.14c
N <sub>2</sub>	正常供水 Sufficient water supply	425.48±8.07b	1.66±0.07ab
	干旱胁迫 Drought stress	354.85±6.23c	1.74±0.12a
N <sub>3</sub>	正常供水 Sufficient water supply	490.02±3.08a	1.71±0.06a
	干旱胁迫 Drought stress	418.40±6.39b	1.75±0.07a
F 值	氮肥 Nitrogen	2155.50 * *	21.55 * *
F value	水分 Water	911.87 * *	1.13
	氮肥×水分 Nitrogen × Water	3.23	5.86 *

3 讨 论

光合作用是植物体内重要的代谢过程,它显著影响作物的生长、产量和抗逆性<sup>[23]</sup>.功能叶片的叶绿素含量直接影响光合速率和光合产物的形成,是反映作物光合能力的一个重要指标.小麦在遭受较长时间干旱或渍水胁迫时,植株发生的共同特征是叶绿素含量下降,叶片衰老加快,光系统Ⅱ(PSⅡ)的最大光化学量子产量( $F_v/F_m$ )和实际光化学量子产量降低,植株光合作用受到抑制<sup>[24-25]</sup>.因此,如何减缓叶片衰老、延长绿叶功能期、延长光合时间是减轻水分胁迫对小麦伤害的有效途径,也是调控籽粒产量的关键.水分胁迫(干旱或渍水胁迫)下,适量追氮可以缓解 $P_n$ 、 $g_s$ 和 $T_r$ 的下降,并能减轻水分胁迫对光合器官的破坏,改善叶片的光合性能<sup>[21,26]</sup>.本试验条件下,N<sub>2</sub>和N<sub>3</sub>处理通过提高水分胁迫下冬小麦旗叶的SPAD,降低旗叶光合速率的下降幅度,进而增加光合产物积累量,减缓逆境对冬小麦的不利影响.另外,本研究中,在开花期,相同供水条件下,除正常供水外,N<sub>2</sub>处理光合速率均高于N<sub>3</sub>处理,这是由于开花期光合速率的测定是在N<sub>3</sub>处理追施开花肥后第4天进行的,此时植株可能处于高氮胁迫状态,这对光合速率有一定的抑制作用,随着生育期的推进,这种胁迫状态逐渐消除,到了灌浆期,追施氮肥对光合速率表现出了促进作用(图2).有研究表明,生育后期过多施氮量会使叶片氮代谢旺盛,造成光合产物输出减少,光合产物对光合器官产生反馈抑制<sup>[27]</sup>.

本研究中,渍水胁迫和干旱胁迫显著降低冬小麦的产量,这主要是因为生育后期渍水胁迫和干旱胁迫显著降低旗叶的叶绿素和光合速率(图1和图2),植株早衰,干物质积累量降低,导致穗粒数和

千粒重显著降低(表1).干物质积累量是产量形成的基础,相同氮肥条件下,干旱胁迫下地上部分生物量最低(表1),因此其产量也最低,这也说明干旱胁迫对产量的影响最严重.渍水胁迫下地上部分生物量虽然较高,但渍水胁迫使植株“库”、“源”器官发育受限,从而抑制干物质向生殖器官输送<sup>[3]</sup>,因此,渍水胁迫处理籽粒产量较正常供水低.水分胁迫下,氮素营养是调控产量的重要措施.干旱胁迫下,适量施氮能够增加植株叶片脯氨酸的累积,增强渗透调节强度<sup>[28]</sup>,提高作物对干旱的适应性.渍水胁迫下,追施氮肥能够提高小麦的灌浆速率从而减轻逆境灾害对产量的不利影响<sup>[29]</sup>.Swarup等<sup>[30]</sup>研究认为,短期渍水胁迫后,与不追施氮肥相比,追施氮肥能够增加小麦地上和地下部分植株干质量、穗数及穗粒数,进而增加生物量及产量.本研究中,相同水分条件下氮肥后移处理增加了冬小麦的地上部分生物量和穗粒数(表1).拔节期至开花期是小麦吸氮的高峰期,追施氮肥可以补充植株生育后期氮素营养,降低不孕小花数,增加穗粒数<sup>[29]</sup>.随着追氮比例的增加,与正常供水相比,渍水胁迫和干旱胁迫处理产量的下降幅度呈降低趋势.叶片的光合能力是决定籽粒产量的一个关键参数<sup>[31]</sup>,N<sub>2</sub>和N<sub>3</sub>处理下渍水胁迫和干旱胁迫处理花后旗叶光合速率下降幅度较低,从而增强光合效率,增加干物质积累,缓解渍水和干旱胁迫对产量的不利影响,追施氮肥对产量表现出了更好的补偿效应.

施氮可以提高作物水分利用效率,且分次施氮或加大追氮比例的效果更为明显<sup>[32-33]</sup>.本研究中,氮肥后移在增加耗水量的同时大幅度提高了产量,显著提高了水分利用效率.谢英荷等<sup>[34]</sup>研究认为,自然降水条件下,追施氮肥虽然增加了土壤耗水量,但也增强了土壤供水量,显著增加了产量,提高了作物的水分利用效率.普遍认为,适度干旱能够增加水

分利用效率<sup>[35-36]</sup>,但也有相反的报道<sup>[37]</sup>,这与干旱胁迫的程度、时间及作物品种的遗传特性有关<sup>[36]</sup>. 本研究中,生育后期持续干旱条件下,干旱胁迫并没有显著提高冬小麦的水分利用效率,其中在  $N_1$  条件下,干旱胁迫下水分利用效率较正常供水显著降低,这与赵世伟等<sup>[35]</sup>的研究结果相似,在冬小麦干旱敏感期(灌浆期)水分亏缺影响有机物液流运输,从而使籽粒灌浆艰难,有机物合成减少,显著降低产量和水分利用效率. 氮肥后移虽然可以显著增加产量<sup>[18]</sup>,但在土壤干旱情况下,氮肥的作用受到极大限制<sup>[38]</sup>,与正常供水相比, $N_2$ 和  $N_3$ 处理下干旱胁迫处理的耗水量和产量均降低,水分利用效率差异不显著.

本研究表明,冬小麦在生育后期遭受渍害或持续干旱胁迫时,氮肥后移通过提高旗叶 SPAD 和减缓花后旗叶光合速率的下降幅度,增加地上部分干物质积累量,调控产量及其构成要素,减轻了逆境灾害对产量的影响.

#### 参考文献

- [1] Liu L (刘玲), Sha Y-Z (沙奕卓), Bai Y-M (白月明). Regional distribution of main agrometeorological disasters and disaster mitigation strategies in China. *Journal of Natural Disasters* (自然灾害学报), 2003, **12**(2): 92-97 (in Chinese)
- [2] Qin DH, Ding YH, Wang SW, *et al.* Ecological and environmental change in west China and its response strategy. *Advances in Earth Science*, 2002, **17**: 314-319
- [3] Cai J (蔡剑), Jiang D (姜东). The effect of climate change on winter wheat production in China. *Journal of Agro-Environment Science* (农业环境科学学报), 2011, **30**(9): 1726-1733 (in Chinese)
- [4] Lu L-P (卢丽萍), Cheng C-L (程从兰), Liu W-D (刘伟东), *et al.* Effect of the agricultural meteorological disasters on agricultural production and its spatial distribution characteristics during the last 30 years in China. *Ecology and Environmental Sciences* (生态环境学报), 2009, **18**(4): 1573-1578 (in Chinese)
- [5] Huang R-H (黄荣辉), Du Z-C (杜振彩). Evolution characteristics and trend of droughts and floods in China under the background of global warming. *Chinese Journal of Nature* (自然杂志), 2010, **32**(4): 187-195 (in Chinese)
- [6] Shao G-C (邵光成), Yu S-E (俞双恩), Liu N (刘娜), *et al.* Study on continuous days of water logging and excessive soil water as drainage index of wheat. *Transactions of the Chinese Society of Agricultural Engineering* (农业工程学报), 2010, **26**(8): 56-60 (in Chinese)
- [7] Sharma PK, Sharma SK, Choi IY. Individual and combined effects of waterlogging and alkalinity on yield of wheat (*Triticum aestivum* L.) imposed at three critical stages. *Physiological and Molecular Biology of Plants*, 2010, **16**: 317-320
- [8] Li CY, Jiang D, Wollenweber B, *et al.* Waterlogging pretreatment during vegetative growth improves tolerance to waterlogging after anthesis in wheat. *Plant Science*, 2011, **180**: 672-678
- [9] Wu J-D (吴进东), Li J-C (李金才), Wei F-Z (魏凤珍), *et al.* Effect of interaction of waterlogging and high temperature after anthesis on photosynthetic characteristics of flag leaf and yield in winter wheat. *Acta Agronomica Sinica* (作物学报), 2012, **38**(6): 1071-1079 (in Chinese)
- [10] Sun H-Y (孙宏勇), Liu C-M (刘昌明), Wang Z-H (王振华), *et al.* Changing trend of precipitation and its effects on crop productivity in the piedmont of Taihang Mountain. *Chinese Journal of Eco-Agriculture* (中国生态农业学报), 2007, **15**(6): 18-21 (in Chinese)
- [11] Xu Z-Z (许振柱), Yu Z-W (于振文), Zhang Y-L (张永丽). The effects of soil moisture on grain starch synthesis and accumulation of winter wheat. *Acta Agronomica Sinica* (作物学报), 2003, **29**(4): 595-600 (in Chinese)
- [12] Irfan M, Hayat S, Hayat Q, *et al.* Physiological and biochemical changes in plants under waterlogging. *Protoplasma*, 2010, **241**: 3-17
- [13] Tan W, Liu J, Dai TB, *et al.* Alterations in photosynthesis and antioxidant enzyme activity in winter wheat subjected to post-anthesis waterlogging. *Photosynthetica*, 2008, **46**: 21-27
- [14] Jiang D (姜东), Xie Z-J (谢祝捷), Cao W-X (曹卫星), *et al.* Effects of post-anthesis drought and waterlogging on photosynthetic characteristics, assimilates transportation in winter wheat. *Acta Agronomica Sinica* (作物学报), 2004, **30**(2): 175-182 (in Chinese)
- [15] Hossain MA, Araki H, Takahashi T, *et al.* Poor grain filling induced by waterlogging is similar to that in abnormal early ripening in wheat in Western Japan. *Field Crops Research*, 2011, **123**: 100-108
- [16] Zhao H (赵辉), Dai T-B (戴廷波), Jiang D (姜东), *et al.* Effects drought and waterlogging on flag leaf post-anthesis photosynthetic characteristics and assimilates translocation in winter wheat under high temperature. *Chinese Journal of Applied Ecology* (应用生态学报), 2007, **18**(2): 333-338 (in Chinese)
- [17] Hu C-D (胡程达), Yang G-X (杨光仙), Cheng L (成林). Effects of drought on distribution and accumulation of photosynthetic matter in winter wheat. *Chinese Journal of Agrometeorology* (中国农业气象), 2014, **35**(3): 243-249 (in Chinese)
- [18] Jiang J-H (蒋家慧). Effects of nitrogen application on carbon assimilation, transfer and yield of the wheat. *Journal of Triticeae Crops* (麦类作物学报), 2004, **24**(3): 69-72 (in Chinese)
- [19] Feng J-F (冯金凤), Zhao G-C (赵广才), Zhang B-J (张宝军), *et al.* Effect of topdressing nitrogen ratio on yield, protein components and physiological characteris-

- tics of winter wheat. *Plant Nutrition and Fertilizer Science* (植物营养与肥料学报), 2013, **19**(4): 824–831 (in Chinese)
- [20] Du S-Z (杜世州), Cao C-F (曹承富), Zhang Y-L (张耀兰), *et al.* Effects of nitrogen application on nitrogen absorption, utilization in super-high-yielding wheat in Huaibei region. *Plant Nutrition and Fertilizer Science* (植物营养与肥料学报), 2011, **17**(1): 9–15 (in Chinese)
- [21] Wu W-M (武文明), Chen H-J (陈洪俭), Li J-C (李金才), *et al.* Effects of nitrogen fertilization on chlorophyll fluorescence parameters of flag leaf and grain filling in winter wheat suffered waterlogging at booting stage. *Acta Agronomica Sinica* (作物学报), 2012, **38**(6): 1088–1096 (in Chinese)
- [22] Fan X-M (范雪梅), Jiang D (姜 东), Dai T-B (戴廷波), *et al.* Effects of nitrogen supply on flag leaf photosynthesis and grain starch accumulation of wheat from its anthesis to maturity under drought or waterlogging. *Chinese Journal of Applied Ecology* (应用生态学报), 2005, **16**(10): 1883–1888 (in Chinese)
- [23] Hui H-X (惠红霞), Xu X (许 兴), Li Q-R (李前荣). Exogenous betaine improves photosynthesis of *Lycium barbarum* under salt stress. *Acta Botanica Boreali-Occidentalia Sinica* (西北植物学报), 2003, **23**(12): 2137–2142 (in Chinese)
- [24] Huseynova IM. Photosynthetic characteristics and enzymatic antioxidant capacity of leaves from wheat cultivars exposed to drought. *Biochimica et Biophysica Acta*, 2012, **1817**: 1516–1523
- [25] Araki H, Hamada A, Hossain MA, *et al.* Waterlogging at jointing and/or after anthesis in wheat induces early leaf senescence and impairs grain filling. *Field Crops Research*, 2012, **137**: 27–36
- [26] Zhang R-H (张仁和), Guo D-W (郭东伟), Zhang X-H (张兴华), *et al.* Effects of nitrogen on photosynthesis and antioxidant enzyme activities of maize leaf under drought stress. *Journal of Maize Sciences* (玉米科学), 2012, **20**(6): 118–122 (in Chinese)
- [27] Kang G-Z (康国璋), Wang Y-H (王永华), Guo T-C (郭天财), *et al.* Effects of nitrogen application on photosynthetic characteristics and yield of super high yielding wheat in the late growing and developing period. *Acta Agronomica Sinica* (作物学报), 2003, **29**(1): 82–86 (in Chinese)
- [28] Zhou P (周 萍), Chen Z-G (陈治国), Zhuang L (庄 丽), *et al.* Effect of irrigation and nitrogen interaction on osmoregulation substances content and yield of drip irrigation wheat. *Journal of Shihezi University* (Natural Science) (石河子大学: 自然科学版), 2013, **31**(4): 425–429 (in Chinese)
- [29] Wu J-D (吴进东), Li J-C (李金才), Wei F-Z (魏凤珍), *et al.* Effects of postponing nitrogen application on grain filling characteristics and yield components of winter wheat suffered waterlogging after anthesis. *Acta Botanica Boreali-Occidentalia Sinica* (西北植物学报), 2013, **33**(3): 570–576 (in Chinese)
- [30] Swarup A, Sharma DP. Influence of top-dressed nitrogen in alleviating adverse effects of flooding on growth and yield of wheat in a sodic soil. *Field Crops Research*, 1993, **35**: 93–100
- [31] Guo ZJ, Yu ZW, Wang D, *et al.* Photosynthesis and winter wheat yield responses to supplemental irrigation based on measurement of water content in various soil layers. *Field Crops Research*, 2014, **166**: 102–111
- [32] Zhao F-H (赵芳华), Zhang S-H (张树华), Guo C-J (郭程瑾), *et al.* Effects of nitrogen application methods on photosynthesis and senescence characteristics of flag leaves in wheat under limited irrigation. *Plant Nutrition and Fertilizer Science* (植物营养与肥料学报), 2009, **15**(2): 247–254 (in Chinese)
- [33] Yi Z-X (易镇邪), Wang P (王 璞), Chen H-B (陈洪斌), *et al.* Effect of base-N/dress-N ratio on water and nitrogen utilization, growth of summer maize in North China Plain. I. Growth, development and water use efficiency of summer maize. *Chinese Journal of Eco-Agriculture* (中国生态农业学报), 2007, **15**(6): 65–68 (in Chinese)
- [34] Xie Y-H (谢英荷), Li T-L (李廷亮), Hong J-P (洪坚平), *et al.* Effects of nitrogen application and ridge film furrow planting on water use of winter wheat in dry land of South Shanxi. *Chinese Journal of Applied Ecology* (应用生态学报), 2011, **22**(8): 2038–2044 (in Chinese)
- [35] Zhao S-W (赵世伟), Guan X-J (管秀娟), Wu J-S (吴金水). Effects of water deficits on yield and WUE in winter wheat. *Irrigation and Drainage* (灌溉排水), 2001, **20**(4): 56–59 (in Chinese)
- [36] Boutraa T, Akhkh A, Al-Shoaibi AA, *et al.* Effect of water stress on growth and water use efficiency (WUE) of some wheat cultivars (*Triticum durum*) grown in Saudi Arabia. *Journal of Taibah University for Science*, 2010, **3**: 39–48
- [37] Liu F, Andersen MN, Jacobsen SE, *et al.* Stomatal control and water use efficiency of soybean (*Glycine max* L. Merr.) during progressive soil drying. *Environmental and Experimental Botany*, 2005, **54**: 33–40
- [38] Zhai B-N (翟丙年), Li S-X (李生秀), Qi Y-T (齐亚婷). Effects of nitrogen fertilizer on winter wheat yield and its component under different status of soil moisture. *Acta Botanica Boreali-Occidentalia Sinica* (西北植物学报), 2001, **21**(3): 462–467 (in Chinese)

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