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测墒补灌条件下高产小麦品种水分利用特性及干物质积累和分配

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摘 要: 2007—2009年连续2个小麦生长季, 利用测墒补灌技术, 设置0~140 cm 土壤相对含水量低(拔节期65%, 开花期55%~60%)、中(拔节期75%, 开花期65%~70%)、高(拔节期75%, 开花期75%) 3个处理, 比较了14个小麦生产品种的水分利用特性及干物质积累和分配的差异。以小麦籽粒产量和水分利用率为指标的聚类分析, 将14个小麦品种分为3组, 分别是超高产高水分利用率组(I 组)、超高产中水分利用率组(II 组)和高产低水分利用率组(III 组)。比较各组代表品种的耗水量、耗水模系数及日耗水量, 播种至拔节期山农15 (I 组)显著低于济麦22 (II 组)和烟农21 (III 组), 拔节至开花期山农15显著高于济麦22和烟农21, 开花至成熟期品种间无显著差异。在中水分条件下, 山农15的土壤贮水消耗量及其占总耗水量的比例显著高于济麦22和烟农21, 而在低和高水分条件下, 3个品种无显著差异。在中、高水分条件下, 山农15开花期的干物质积累量显著高于济麦22和烟农21, 成熟期与济麦22无显著差异, 但显著高于烟农21; 营养器官开花前贮藏同化物向籽粒的转运量和转运率及对籽粒的贡献率均显著高于济麦22和烟农21; 3个品种的经济系数以山农15最大, 济麦22次之, 烟农21最小。

关键词: 测墒补灌; 产量; 水分利用率; 干物质积累与分配

Characteristics of Water Use and Dry Matter Accumulation and Distribution in Different High-yielding Wheat Cultivars under Supplemental Irrigation Based on Soil Moisture

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Abstract: Water shortage is a serious problem threatening sustainable agricultural development in the North China Plain, where winter wheat (*Triticum aestivum* L.) is the largest water-consuming crop. The objective of this study was to guide wheat production in this area by selecting high water efficient cultivar and improving irrigation regime. In a two-year field experiment from autumn of 2007 to summer of 2009, irrigation quantum was controlled based on testing soil moisture (SM) in 0–140 cm depth, which was designed in low (SM of 65% at jointing and 55%–60% at anthesis stage), medium (SM of 75% at jointing and 65%–70% at anthesis stage), and high (SM of 75% at jointing and 75% at anthesis stage) levels. Water use efficiency (WUE), dry matter accumulation and distribution in wheat plant, and grain yield were tested and compared among 14 commercial cultivars. Based on grain yield and WUE, the 14 cultivars were clustered into three groups, namely, super-high yield and high WUE group (I), super-high yield and medium WUE group (II), and high yield and low WUE group (III). One representative cultivar was selected from each group to compare the amount and proportion of water consumption during sowing–jointing, jointing–anthesis, and anthesis–maturity periods. Shannong 15 from group I had significantly lower water consumption from sowing to jointing than Jimai 22 from group II and Yannong 21 from group III, and significantly higher water consumption from jointing to anthesis. However, water consumption amount and proportion had no significant differences among the three cultivars from anthesis to

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maturity. Under medium SM condition, soil water consumption in Shannong 15 was significantly higher than that in Jimai 22 and Yannong 21, but such advantage in Shannong 15 disappeared under high SM condition. Under medium and high SM conditions, translocation amount and ratio of dry matter accumulated before anthesis and its contribution to grain were significantly higher in Shannong 15 than in Jimai 22 and Yannong 21. Among the three cultivars, harvest index was the highest in Shannong 15, the medium in Jimai 22, and the lowest in Yannong 21.

Keywords: Irrigation based on testing soil moisture; Yield; Water use efficiency; Dry matter accumulation and distribution

我国人均水资源拥有量为世界平均值的1/4, 是世界上13个严重缺水的国家之一[1]。华北小麦主产区水资源的严重匮乏已经成为该地区小麦生产的主要限制因素, 如何合理利用有限的水资源、减少灌溉用水、提高水分利用率是小麦生产迫切需要解决的问题[2]。研究表明, 通过调控灌水量[3-5]、灌水时期[6-7]、灌水方法[8-9]形成适度水分胁迫, 小麦可获得较高的产量和水分利用率, 达到节水高产的目的。

水高效生理和遗传机制在不同小麦品种间差异较大[10-11], 小麦籽粒产量差异可达44.9%, 水分利用率差异为42.2%[12]。多穗型小麦品种叶片对籽粒产量的贡献大于大穗型品种[13], 大穗型品种在灌浆中后期比多穗型品种具有更强的淀粉合成能力, 但对水分较为敏感[14]。旱地品种一般在不灌溉条件下水分利用率较高; 水旱兼用型品种在灌溉较少(返青后灌水1次)条件下水分利用率最大; 而水地品种则一般在充分灌溉(返青后灌水2~3次)条件下, 水分利用率和产量协同达到最优[15]。

节水灌溉是华北平原小麦高产栽培中推广的关键技术之一, 但是高产条件下不同水浇地品种在各生育阶段的耗水特性、水分利用率及干物质积累与分配的差异尚不清楚。本试验以生产中推广的14个小麦品种为材料, 采用测墒补灌的方法, 研究不同高产品种的水分利用特性及干物质积累与分配的差异, 为小麦生产中选择高产和水分利用率高的品种、完善高产节水栽培技术体系提供理论依据。

1 材料与方法

1.1 试验地概况

山东泰安山东农业大学试验农场地处暖温带大陆性半湿润季风气候, 年均气温13℃, 年均降水量675.3 mm。试验地为沙壤土, 小麦播种前0~20 cm土层含有机质1.36%、全氮0.85%、碱解氮79.40 mg kg^{-1}、速效磷38.20 mg kg^{-1}、速效钾80.00 mg kg^{-1}。0~20、20~40、40~60、60~80、80~100、100~120、120~140、140~160、160~180和180~200 cm土层土壤田间持水量分别为25.92%、25.11%、24.35%、25.20%、24.56%、24.05%、24.98%、24.87%、25.01%和24.76%, 土壤容重分别为1.51、1.52、1.54、1.56、1.55、1.57、1.57、1.58、1.59和1.59 g cm^{-3}。

1.2 试验材料

2007—2008年度小麦生长季, 选用14个山东省选育的生产品种, 分别是良星99、烟农21、烟2415、烟5158、烟5286、山农15、洲元9369、济麦22、泰9818、临麦4号、汶农6号、潍麦8号、聊麦19和山农8355。以籽粒产量和水分利用率为指标, 对这14个品种作聚类分析, 将其分为3组。2008—2009年度每组选择1个代表性品种(山农15、济麦22和烟农21)作进一步试验。

1.3 试验设计

按0~140 cm土壤平均相对含水量设置低土壤含水量(LSM)、中土壤含水量(MSM)和高土壤含水量(HSM) 3个水分处理, 两年度自然降水和灌溉量见表1。用土钻取0~200 cm土层, 每20 cm为一层, 将样品立即装入铝盒, 称鲜质量; 然后110℃烘干至恒质量, 称干质量。土壤质量含水量(%) = (土壤鲜质量–土壤干质量)/土壤干质量×100; 土壤相对含水量(%) = 土壤质量含水量/田间持水量×100; 用环刀法[16]测定田间持水量。灌水量(mm)由$m = 10 \times \rho b \times H \times (\beta_i - \beta_j)$计算得出[17], 式中$m$为灌水量(mm), H为该时段土壤计划湿润层的深度(本试验为140 cm), ρb为计划湿润层内土壤容重(g cm^{-3}), β_i为设计含水量(田间持水量乘以目标相对含水量), β_j为自然含水量, 即灌溉前土壤含水量。用水表计灌水量。

采用裂区设计, 主区为土壤相对含水量, 副区为品种, 小区间设1.0 m隔离区, 小区面积均为4 m × 4 m=16 m^2, 3次重复。2007年10月10日播种, 2008年6月10日收获; 2008年10月8日播种, 2009年6月10日收获。四叶期定苗至195株 m^{-2}。两年度均在播种前施纯氮105 kg hm^{-2}、P_2O_5 112.5 kg hm^{-2}和K_2O 112.5 kg hm^{-2}, 拔节期开沟追施纯氮135 kg hm^{-2}。生长期按当地高产田进行田间管理。

1.4 耗水量计算方法

测定0~200 cm土层土壤水分含量变化, 根据SPAC理论用农田水分平衡法[18]计算耗水量。

表 1　2007–2008 和 2008–2009 两年度自然降水量和灌溉量
Table 1　Precipitations and irrigation quantities in 2007–2008 and 2008–2009 wheat growing seasons (mm)

生育阶段 Growing period		2007–2008	2008–2009
降水量 Precipitation			
播种–越冬前 Sowing–before overwintering		28.3	14.8
越冬前–返青 Before overwintering–regreening		15.1	10.9
返青–拔节 Regreening–jointing		17.7	18.0
拔节–开花 Jointing–anthesis		68.2	54.0
开花–成熟 Anthesis–maturity		40.5	47.0
灌水量 Irrigation			
LSM	拔节期 Jointing	0	0
	开花期 Anthesis	0	0
MSM	拔节期 Jointing	53.8–65.8 a)	66.6–70.3 c)
	开花期 Anthesis	0	0
HSM	拔节期 Jointing	53.8–65.8 a)	66.6–70.3 c)
	开花期 Anthesis	53.3–63.6 b)	27.1–40.0 d)

低(LSM)、中(MSM)、高土壤含水量(HSM)处理均为 0~140 cm 土壤平均相对含水量, 2007–2008 年度依次为拔节期 65%+开花期 55%、拔节期 75%+开花期 65%和拔节期 75%+开花期 75%, 2008–2009 年度依次为拔节期 65%+开花期 60%、拔节期 75%+开花期 70%和拔节期 75%+开花期 75%。2007–2008 年度, MSM 处理的开花期自然含水量已达到设计要求(65%), 所以开花期未补灌。2008–2009 年度, MSM 处理开花期土壤含水量高于上年度设计水平, 是由于该年度开花期前降雨导致开花期土壤相对含水量较高, 不补灌也达到 70%。2007–2008 年度, 14 个品种(良星 99、烟农 21、烟 2415、烟 5158、烟 5286、山农 15、洲元 9369、济麦 22、泰 9818、临麦 4 号、汶农 6 号、潍麦 8 号、聊麦 19 和山农 8355)的实际灌水量分别为 a) 65.8、61.1、58.4、59.9、53.8、57.3、65.3、61.1、59.9、65.3、53.8、60.2、61.1 和 58.4 mm; b) 56.8、56.8、55.6、55.6、57.7、57.5、58.9、63.6、53.3、57.7、57.5、56.8、56.8 和 57.6 mm。2008–2009 年度, 3 个品种(山农 15、济麦 22 和烟农 21)的实际灌水量分别为 c) 66.6、70.3 和 67.0 mm; d) 40.0、31.7 和 27.1 mm。

Low (LSM), medium (MSM), and high soil moisture (HSM) treatments were designed according to the relative soil water content in 0–140 soil layers, with soil moisture (SM) at joining + anthesis of 65% + 55%, 75% + 65%, and 75% +75% in 2007–2008 growing season and 65% + 60%, 75% + 70%, and 75% + 75% in 2008–2009 growing season, respectively. In the 2007–2008 growing season, zero irrigation was conducted at anthesis stage in MSM treatment because natural SM had reached the designed level (65%). The designed SM at anthesis in 2008–2009 was higher than that in 2007–2008, because precipitation occurred before anthesis, which resulted in SM of 70% without supplementary irrigation. The actual amounts of irrigation for 14 cultivars (Liangxing 99, Yannong 21, Yan 2415, Yan 5158, Yan 5286, Shannong 15, Zhouyuan 9369, Jimai 22, Tai 9818, Linmai 4, Wennong 6, Weimai 8, Liaomai 19, and Shannong 8355) used in 2007–2008 were a) 65.8, 61.1, 58.4, 59.9, 53.8, 57.3, 65.3, 61.1, 59.9, 65.3, 53.8, 60.2, 61.1, and 58.4 mm, respectively; b) 56.8, 56.8, 55.6, 55.6, 57.7, 57.5, 58.9, 63.6, 53.3, 57.7, 57.5, 56.8, 56.8, and 57.6 mm, respectively. The actual amounts of irrigation for 3 cultivars (Shannong 15, Jimai 22, and Yannong 21) used in 2008–2009 were c) 66.6, 70.3, and 67.0 mm, respectively; d) 40.0, 31.7, and 27.1 mm, respectively.

作物生育期耗水量:

$$ET\alpha = P + U - R - F + \Delta W + I \quad (1)$$

式中, ΔW为土壤贮水消耗量; P为该时段降水量(mm); U为地下水通过毛管作用上移补给作物水量(mm); R为地表径流量(mm); F为补给地下水量(mm); I为灌水量(mm)。本试验地块地势平坦, 地下水埋深5 m以下, 降水入渗深度不超过2 m, 因此U、R、F均为0; 本试验以20 cm为一个土壤层次。

$$ET_{1-2} = 10\sum_{i=1}^{n}\gamma_i H_i(\theta_{i1} - \theta_{i2}) + I + P \quad (2)$$

式中, i为土层编号; n为总土层数; γ_i为第i层土壤容重; H_i为第i层土壤厚度; θ_{i1}和θ_{i2}为第i层土壤时段初和时段末的含水量, 以占干土重的百分数计; I为时段内的灌水量; P为该时段内的降水量。

1.5　干物质转运和水分利用率计算方法

开花期按叶、茎+叶鞘和穗取样, 成熟期按叶、茎+叶鞘、穗轴+颖壳和籽粒取样, 3次重复, 75℃烘至恒重, 称干重, 计算同化物转运量和转运率[19]。营养器官开花前贮藏同化物转运量=开花期干重–成熟期干重; 营养器官开花前贮藏同化物转运率(%) = (开花期干重–成熟期干重)/开花期干重×100; 开花后同化物输入籽粒量=成熟期籽粒干重–营养器官花前贮藏物质转运量; 对籽粒产量的贡献率(%) =开花前营养器官贮藏物质转运量/成熟期籽粒干重× 100。水分利用率(kg hm^{-2} mm^{-1}) = 籽粒产量(kg hm^{-2})/作物全生育期耗水量(mm) [20]。

1.6　数据分析

用Microsoft Excel 2003处理数据和绘图, 用DPS7.5软件进行数据统计分析和差异显著性检验, 用DPS7.5数据分析软件进行数据标准化转化, 根据欧氏距离的大小, 运用最长距离法, 对供试品种作聚类分析。

2 结果与分析

2.1 不同小麦品种籽粒产量及水分利用率的差异

以2007—2008年度生长季籽粒产量和水分利用率为指标，通过聚类分析将14个品种分成3组(图1)，分别是超高产高水分利用率组(I)、超高产中水分利用率组(II)和高产低水分利用率组(III)。本文将单产超过9000 kg hm^{-2}的品种称为超高产品种[21]，单产7500~9000 kg hm^{-2}的称为高产品种。

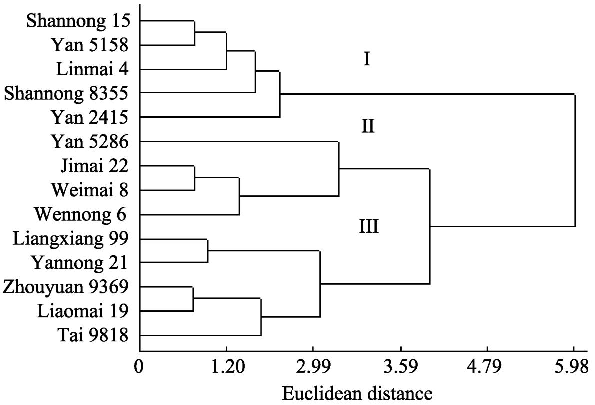

图 1 基于籽粒产量和水分利用率的品种聚类图

Fig. 1 Dendrogram of wheat cultivars based on grain yield and water use efficiency

I: 超高产高水分利用率组; II: 超高产中水分利用率组; III: 高产低水分利用率组。

I: super-high yield and high WUE group; II: super-high yield and medium WUE group; III: high yield and low WUE group.

随开花期土壤相对含水量增加，水分利用率呈降低的趋势。I和III组品种的籽粒产量平均值在MSM和HSM处理间无显著差异，均显著高于LSM处理；而II组各品种籽粒产量则表现为HSM > MSM > LSM，处理间有显著差异(表2)。表明不同组别获得超高产或高产的需水特性存在差异，I组在开花期土壤含水量较低条件下即能获得超高产，而II组开花期要求的土壤相对含水量较高。

2008—2009年度，对3个代表性品种的籽粒产量和水分利用率进行了测定，其结果趋势与上年度相同(表3)，因此以这3个品种分别代表其所在组进行水分利用特性及干物质积累分配的分析。

2.2 不同小麦品种耗水量的水分来源及其占总耗水量的比例

随开花期土壤相对含水量增加，3个品种均表现为总耗水量增加，土壤贮水消耗量及其占总耗水量的比例降低，灌溉水占总耗水量的比例增加(表4)，表明降低开花期土壤相对含水量有利于小麦利用降水和土壤贮水。

在LSM和HSM条件下，3个品种的总耗水量及土壤水消耗量占总耗水量的比例均无显著差异；在MSM条件下，山农15的总耗水量、土壤水消耗量及占总耗水量的比例均显著高于济麦22和烟农21，表明在MSM条件下，山农15有较高的利用土壤贮水能力。

2.3 不同小麦品种各生育阶段的耗水量、耗水模系数和日耗水量

不同处理播种至拔节期的耗水量和日耗水量无显著差异，耗水模系数为LSM>MSM>HSM；拔节至开花期，耗水量、耗水模系数和日耗水量在MSM和HSM处理间无显著差异，显著高于LSM处理；开花至成熟期的耗水量、耗水模系数和日耗水量均为HSM处理最高(表5)。不同土壤相对含水量对3个品种的拔节至开花期和开花至成熟期耗水特性的调控效应不同，可能是导致不同品种各处理的总耗水量不同的主要原因。

在同一处理中，山农15播种至拔节期的耗水量、耗水模系数及日耗水量显著低于济麦22和烟农21，拔节至开花期显著高于济麦22和烟农21，开花至成熟期与济麦22和烟农21无显著差异(表5)。表明不同品种在各个生育阶段的耗水强度存在差异，山农15拔节前耗水量少，拔节至开花期通过高效吸收土壤贮水提高了耗水量，有利于此阶段小花的成熟发育，防止小花退化，提高山农15的分蘖成穗率和穗粒数。

2.4 不同小麦品种干物质积累及分配

3个品种开花期和成熟期干物质积累量均为MSM和HSM处理无显著差异，显著高于LSM处理。山农15和烟农21的经济系数为LSM>MSM>HSM，处理间差异显著；济麦22为LSM显著高于MSM和HSM处理，MSM和HSM处理间无显著差异(表6)。表明灌溉降低了成熟期干物质积累量向籽粒的分配比例。随开花期土壤相对含水量提高，营养器官开花前贮藏同化物向籽粒的转运量和转运率及对籽粒的贡献率均显著降低，表现为LSM>MSM>HSM，开花后干物质积累量及其对籽粒的贡献率则相反。表明提高开花期土壤相对含水量促进了开花后干物质积累及向籽粒转运，不利于开花前贮藏同化物向籽粒的转运。

在LSM条件下，山农15和济麦22开花期和成熟期干物质积累量均显著高于烟农21；MSM和HSM

表 2　不同小麦品种籽粒产量和水分利用率(2007–2008)
Table 2　Grain yield and water use efficiency of different wheat cultivars in 2007–2008

组 Group	品种 Cultivar	LSM		MSM		HSM	
		GY ($kg\ hm^{-2}$)	WUE ($kg\ hm^{-2}\ mm^{-1}$)	GY ($kg\ hm^{-2}$)	WUE ($kg\ hm^{-2}\ mm^{-1}$)	GY ($kg\ hm^{-2}$)	WUE ($kg\ hm^{-2}\ mm^{-1}$)
I	山农 15 Shannong 15	8395.0	22.4	9074.8	21.9	9221.4	20.6
	烟 5158 Yan 5158	8361.9	22.1	9014.5	21.8	9292.6	21.9
	临麦 4 号 Linmai 4	8544.4	22.2	9109.0	22.1	9602.2	20.2
	山农 8355 Shannong 8355	8274.4	22.5	9330.8	21.5	9092.7	20.4
	烟 2415 Yan 2415	8574.6	22.9	9116.6	21.8	9185.9	20.9
II	烟 5286 Yan 5286	7633.7	19.9	8341.2	20.5	9313.0	20.4
	济麦 22 Jimai 22	8061.1	21.6	8465.2	20.0	9171.7	20.1
	潍麦 8 号 Weimai 8	8096.2	21.3	8679.3	20.4	9057.5	20.1
	汶农 6 号 Wennong 6	8427.8	21.5	8523.0	20.9	9097.3	19.8
III	良星 99 Liangxing 99	8108.8	20.3	8525.6	20.7	8455.3	18.6
	烟农 21 Yannong 21	7887.8	20.5	8521.6	20.0	8413.3	18.5
	洲元 9369 Zhouyuan 9369	7697.3	20.3	8131.1	19.0	8355.6	18.6
	聊麦 19 Liaomai 19	7638.6	20.1	8198.1	18.9	8156.3	19.1
	泰 9818 Tai 9818	7363.6	19.8	7974.0	20.1	8429.9	18.7
I 组平均 I group average		8430.1 a	22.4 a	9129.1 a	21.8 a	9279.0 a	20.8 a
II 组平均 II group average		8054.7 b	21.1b	8502.2 b	20.5 b	9159.9 a	20.1 b
III 组平均 III group average		7739.2 c	20.2 c	8270.1 c	19.7 c	8362.1 b	18.7 c

LSM: 低土壤含水量; MSM: 中土壤含水量; HSM: 高土壤含水量; GY: 籽粒产量; WUE: 水分利用效率。平均值后不同字母表示相同土壤水分条件下品种组间差异达 0.05 显著水平。

LSM: low soil moisture; MSM: medium soil moisture; HSM: high soil moisture; GY: grain yield; WUE: water use efficiency. Different letters after averages indicate significant difference ($P < 0.05$) among cultivar groups under the same soil moisture.

表 3　不同小麦品种籽粒产量和水分利用率(2008–2009)
Table 3　Grain yield and water use efficiency of different wheat cultivars in 2008–2009

品种 Cultivar	LSM		MSM		HSM	
	GY ($kg\ hm^{-2}$)	WUE ($kg\ hm^{-2}\ mm^{-1}$)	GY ($kg\ hm^{-2}$)	WUE ($kg\ hm^{-2}\ mm^{-1}$)	GY ($kg\ hm^{-2}$)	WUE ($kg\ hm^{-2}\ mm^{-1}$)
山农 15 Shannong 15	8082.9 a	21.7 a	9163.4 a	20.9 a	9182.1 a	20.4 a
济麦 22 Jimai 22	7538.7 b	20.4 b	8660.3 b	20.1 b	9005.8 a	19.8 b
烟农 21 Yannong 21	7326.6 c	19.7 c	8150.6 c	19.3 c	8317.7 b	18.8 c

LSM: 低土壤含水量; MSM: 中土壤含水量; HSM: 高土壤含水量; GY: 籽粒产量; WUE: 水分利用效率。数据后不同字母表示相同土壤水分条件下品种间差异达 0.05 显著水平。

LSM: low soil moisture; MSM: medium soil moisture; HSM: high soil moisture; GY: grain yield; WUE: water use efficiency. Different letters after data indicate significant difference ($P < 0.05$) among cultivars under the same soil moisture.

条件下，山农15开花期干物质积累量显著高于济麦22和烟农21，成熟期则表现为山农15和济麦22显著高于烟农21。LSM条件下，经济系数为山农15>烟农21>济麦22，MSM和HSM条件下，经济系数为山农15>济麦22>烟农21，各品种差异显著(表6)，表明产量和水分利用率高的品种其经济系数亦较高。各水分处理下，山农15营养器官开花前贮藏同化物向籽粒的转运量和转运率及对籽粒的贡献率均显著高于济麦22和烟农21，开花后干物质积累量及其对籽粒的贡献率则相反。表明山农15开花期和成熟期均具有较高的干物质积累量，经济系数较高，且开花期前贮藏同化物向籽粒的转运能力较强，为其获得超高产奠定了物质基础。

综合分析耗水特性可见，拔节至开花期耗水量

表 4 不同小麦品种的耗水来源及其占总耗水量的比例(2008–2009)
Table 4 Source of water consumed during wheat growth and its proportion to total water consumption in different cultivars in 2008–2009

处理 Treatment	总耗水量 Total water consumption (mm)	土壤水消耗 Soil water consumption		灌溉 Irrigation		降水 Precipitation	
		消耗量 Amount (mm)	比例 Proportion (%)	灌溉量 Amount (mm)	比例 Proportion (%)	降水量 Amount (mm)	比例 Proportion (%)
山农 15 Shannong 15							
LSM	372.8 e	230.0 a	61.7 a	—	—	142.8	38.3 a
MSM	437.5 b	228.1 a	52.1 b	66.6 c	15.2 c	142.8	32.6 b
HSM	450.4 a	201.0 c	44.6 d	106.6 a	23.7 a	142.8	31.7 b
济麦 22 Jimai 22							
LSM	369.4 e	226.6 a	61.3 a	—	—	142.8	38.7 a
MSM	430.6 c	217.5 b	50.5 c	70.3 c	16.3 c	142.8	33.2 b
HSM	454.1 a	209.3 bc	46.1 d	102.0 a	22.5 a	142.8	31.5 b
烟农 21 Yannong 21							
LSM	371.5 e	228.7 a	61.6 a	—	—	142.8	38.4 a
MSM	422.2 d	212.4 b	50.3 c	67.0 c	15.9 c	142.8	33.8 b
HSM	441.5 ab	204.6 c	46.3 d	94.1 b	21.3 b	142.8	32.4 b

LSM: 低土壤含水量; MSM: 中土壤含水量; HSM: 高土壤含水量。同一列数据后不同字母表示差异达 0.05 显著水平。

LSM: low soil moisture; MSM: medium soil moisture; HSM: high soil moisture. Values followed by different letters in the same column are significantly different at $P < 0.05$.

表 5 不同品种小麦各生育阶段的耗水量、耗水模系数和日耗水量(2008–2009)
Table 5 Water consumption amount, water consumption percentage and water consumption per day of different wheat cultivates in different growing periods in 2008–2009

处理 Treatment	播种至拔节期 Sowing–jointing			拔节至开花期 Jointing–anthesis			开花至成熟期 Anthesis–maturity		
	CA (mm)	CP (%)	CD (mm)	CA (mm)	CP (%)	CD (mm)	CA (mm)	CP (%)	CD (mm)
山农 15 Shannong 15									
LSM	127.6 b	34.2 b	0.7 b	110.0 c	29.5 b	3.6 c	135.2 c	36.3 b	3.5 c
MSM	127.6 b	29.2 d	0.7 b	144.7 a	33.1 a	4.7 a	165.2 b	37.8 b	4.2 b
HSM	127.6 b	28.3 e	0.7 b	144.7 a	32.1 a	4.7 a	178.1 a	39.5 a	4.6 a
济麦 22 Jimai 22									
LSM	143.9 a	39.0 a	0.8 a	87.0 d	23.6 d	2.8 e	138.5 c	37.5 b	3.6 c
MSM	143.9 a	33.4 b	0.8 a	125.8 b	29.2 b	4.1 b	161.0 b	37.4 b	4.1 b
HSM	143.9 a	31.7 c	0.8 a	125.8 b	27.7 c	4.1 b	184.4 a	40.6 a	4.7 a
烟农 21 Yannong 21									
LSM	139.9 a	37.7 a	0.8 a	93.9 d	25.3 c	3.0 d	137.7 c	37.1 b	3.5 c
MSM	139.9 a	33.2 b	0.8 a	125.0 b	29.6 b	4.0 b	157.3 b	37.3 b	4.0 b
HSM	139.9 a	31.7 c	0.8 a	125.0 b	28.3 b	4.0 b	176.6 a	40.0 a	4.5 a

LSM: 低土壤含水量; MSM: 中土壤含水量; HSM: 高土壤含水量; CA: 各生育阶段麦田耗水量; CP: 耗水模系数; CD: 日耗水量。同一列数据后不同字母表示差异达 0.05 显著水平。

LSM: low soil moisture; MSM: medium soil moisture; HSM: high soil moisture; CA: water consumption amount in growth stages; CP: water consumption percentage; CD: water consumption amount per day. Values in the same column followed by different letters are significantly different at $P < 0.05$.

较高的品种山农15, 开花期干物质积累量亦较高, 此类品种可通过提高开花前贮藏同化物向籽粒的转运量和经济系数获得高产, 达到节水高产的目的。本试验条件下, 综合考虑籽粒的产量、水分利用率及灌水量, I组的品种为超高产节水品种, MSM处理是节水高产的最优处理。

表 6　不同品种小麦花后营养器官干物质积累量和干物质再分配量(2008–2009)

Table 6　Dry matter accumulation and translocation amount of vegetative organ after anthesis in different wheat cultivars in 2008–2009

处理 Treatment	DMAAA (kg hm^{-2})	DMAAM (kg hm^{-2})	HI (%)	DMDBA			DMAAA	
				TA (kg hm^{-2})	TR (%)	CG (%)	AA (kg hm^{-2})	CG (%)
山农 15 Shannong 15								
LSM	11024.9 c	15925.5 c	50.8 a	3182.2 a	28.9 a	39.4 a	4900.7 e	60.6 f
MSM	13217.4 a	19348.1 a	47.4 c	3032.7 b	22.9 c	33.1 b	6130.7 c	66.9 e
HSM	13132.8 a	19898.0 a	46.1 d	2416.9 d	18.4 d	26.3 d	6765.2 b	73.7 c
济麦 22 Jimai 22								
LSM	11031.9 c	15873.7 c	47.5 c	2696.8 c	24.5 b	35.8 b	4841.8 e	64.2 e
MSM	12509.3 b	19048.2 a	45.5 e	2121.4 f	17.0 e	24.5 e	6538.9 b	75.5 b
HSM	12548.3 b	19897.7 a	45.3 e	1656.4 f	13.2 f	18.4 f	7349.4 a	81.6 a
烟农 21 Yannong 21								
LSM	9906.0 d	14970.4 e	48.9 b	2262.1 e	22.8 c	30.9 c	5064.4 d	69.1 d
MSM	12172.7 b	18151.9 b	44.9 f	2171.3 f	17.8 d	26.6 d	5979.2 c	73.4 c
HSM	12217.3 b	18903.6 b	44.0 g	1631.5 g	13.4 f	19.6 f	6686.2 b	80.4 a

DMAAA: 开花期干物质积累量; DMAAM: 成熟期干物质积累量; HI: 经济系数; DMDBA: 营养器官花前贮藏干物质; TA: 转运量; TR: 转运率; CG: 籽粒贡献率; DMAAA: 花后同化的干物质; AA: 积累量; LSM: 低土壤含水量; MSM: 中土壤含水量; HSM: 高土壤含水量。同一列数据后不同字母表示差异达 0.05 显著水平。

DMAAA: dry matter accumulative amount at anthesis stage; DMAAM: dry matter accumulative amount at maturity stage; HI: harvest index; DMDBA: dry matter deposit before anthesis; TA: translocation amount; TR: translocation ratio; CG: contribution to grain; DMAAA: dry matter assimilated after anthesis; AA: assimilation amount; LSM: low soil moisture; MSM: medium soil moisture; HSM: high soil moisture. Values in the same column followed by different letters are significantly different at $P < 0.05$.

3　讨论

已有很多试验探讨小麦节水高产的灌水量和灌水次数[12,22-25]。研究表明, 在一定范围内增加灌水量具有增产效应, 但过多灌水导致籽粒产量和水分利用率显著降低[24-25]。表明在一定灌水量范围内, 产量和水分利用率有一个最佳值, 且不同品种获得最佳值时的灌水量和灌水次数不同[12]。樊廷录等[26]用12个旱地品种研究, 发现不同品种产量和水分利用率存在显著差异, 冯广龙和刘昌明[27]指出根系的分布与发育显著影响小麦品种的水分利用率。水分利用率与产量呈正相关, 种植具有较高产量潜力的品种是提高水分利用率并达到节水效果的一种有效途径[28]。在华北地区, 正常年(全生育期降水量140 mm)小麦全生育期灌溉60 mm、干旱年(全生育期降水量73.8 mm)灌溉150 mm、丰水年(全生育期降水量200.8 mm)不灌水可获得较高的产量和水分利用率[29]。本试验以14个水浇地小麦品种为试验材料, 在小麦全生育期降水量169.8 mm条件下, 利用测墒补灌的方法, 将其聚类分为3组, 其中超高产高水分利用率组(I组)山农15、临麦4号等在MSM条件下获得较高产量和水分利用率, 超高产中水分利用率组(II组)济麦22、汶农6号等在HSM条件下获得较高产量, 高产低水分利用率组(III组)烟农21、良星99等则在MSM条件下产量和水分利用率较高, 但显著低于I组和II组。本研究明确了I组在MSM条件下获得较高的产量和水分利用率, 为选用节水高产小麦品种及其获得节水高产的适宜土壤相对含水量的调控提供了依据。不同年际间小麦各生育时期降水量不同对小麦产量和水分利用效率也产生显著影响, 有待进一步研究。

在高产条件下, 冬小麦的产量和耗水量之间呈非线性关系[30-31], Li等[32]认为在中等干旱条件下冬小麦耗水量大幅度下降, 而产量下降幅度较小, 有利于水分利用率的提高。不同小麦品种比较, 在灌水条件相同时品种间全生育期耗水量无显著差异, 产量和水分利用率差异显著[33]; 另有研究指出, 即使全生育期的总耗水量相同, 各生长阶段的分配比例不同, 产量亦不相同[34], 节水抗旱型小麦耗水动态与喜肥型品种相似, 表现前期耗水少, 中后期耗水多的特点[35]。本试验结果表明, 不同品种间的总耗水量及阶段耗水量均存在差异, 在相同灌水条件下, 山农15和济麦22的总耗水量显著高于烟农21; 山农15拔节前耗水少, 拔节至开花期耗水量较高,

开花至成熟期，与济麦22和烟农21无显著差异，表明山农15前期耗水少，中后期耗水多，有利于穗器官的发育和籽粒的充分灌浆，是其获得节水高产的主要原因。山农15拔节至开花期耗水量较高主要是因为其利用了较多的土壤贮水，这是否与此类品种的生长特性和根系分布有关，有待进一步研究。

小麦在某些生育时期水分相对不足或有限亏缺，有利于同化物向籽粒转运，提高经济系数[36]，灌浆期水分亏缺可促进营养器官开花前贮藏干物质向籽粒的再转运[22,37]。在拔节和开花期亏缺灌溉条件下，产量和水分利用率的提高主要是由于增加了灌浆期叶片的净光合速率和光合功能持续期，促进花前储存碳库的再转运，显著提高了经济系数[38]。例如，与西风20相比，抗旱品种石家庄8号能够在较强干旱胁迫下生产较高的干物质获得高产[29]。本研究结果为，MSM和HSM条件下，山农15的开花期干物质积累量显著高于济麦22和烟农21，成熟期则表现为山农15和济麦22显著高于烟农21，经济系数为山农15>济麦22>烟农21。表明山农15在开花期土壤相对含水量为65%~70%条件下，开花期和成熟期较高的干物质积累量、较高经济系数和较高的营养器官开花前贮藏同化物向籽粒的转运量和转运率及对籽粒的贡献率，是其获得节水高产的主要原因。

4 结论

以小麦籽粒产量和水分利用率为指标，将14个小麦品种分为超高产高水分利用率组(I 组)、超高产中水分利用率组(II 组)和高产低水分利用率组(III 组)。在 MSM 条件下，I 组品种山农15的土壤贮水消耗量及占总耗水量的比例、拔节至开花期的耗水量、开花期干物质积累量、经济系数以及开花前贮藏同化物向籽粒的转运量均显著高于 II 组品种济麦22和 III 组品种烟农21。在本试验条件下，I 组品种为超高产节水品种，MSM 处理是节水高产的最优处理。

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