

南疆矮砧密植滴灌苹果生长、耗水及产量研究

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摘要:【目的】提高南疆苹果水分利用率和制定高产高效的灌溉模式。【方法】2019—2020年以5年生矮砧密植皇家嘎拉为研究对象, 设置W₁(13.5 mm)、W₂(18 mm)、W₃(22.5 mm)、W₄(27 mm)及W₅(31.5 mm)5个灌水定额, 研究不同灌水定额对苹果生长、耗水特性、产量及水分利用效率的影响。【结果】苹果新梢长度随灌水定额的增加而增加, 达显著水平($p < 0.05$); 各灌水处理间耗水量、耗水强度及作物系数均随灌水定额的增加而增大, 呈显著差异性($p < 0.05$), 且随生育期推进, 耗水量、耗水强度及作物系数呈单峰曲线, 果实膨大期达到峰值; 苹果产量以W₄处理最高, W₃处理次之, 两年均值分别为30 540.8 kg·hm⁻²和31 144 kg·hm⁻², 两处理产量无显著差异, 水分利用效率以W₁处理最高, W₄和W₅处理较高, 两年均值分别为6.59 kg·m⁻³、6.46 kg·m⁻³和5.49 kg·m⁻³, 灌溉水利用效率与水分利用效率变化规律一致, 并通过拟合分析可知, 水分利用效率和灌溉水利用效率随灌水量增加呈下降趋势, 产量、WUE和IWUE与灌水量拟合曲线交点所对应的灌水量区间为400~500 mm。【结论】综合苹果生长、耗水、产量及水分利用效率分析可知, 生育期灌水定额为22.5 mm, 灌水次数21次为南疆矮砧密植苹果适宜的灌溉模式。

关键词: 苹果; 矮砧密植; 耗水; 产量; 水分利用效率

中图分类号:S661.1

文献标志码:A

文章编号:1009-9980(2021)05-0681-11

Study on the growth, water consumption and yield of drip-irrigated apple trees with dwarfing rootstock and close planting in South Xinjiang

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Abstract: 【Objective】In southern Xinjiang, evaporation is strong and rainfall is scarce. Water resource is extremely limited. This study was carried out in order to improve water use efficiency and develop high-yield and efficient water management programs. 【Methods】In this experiment, 5-year-old densely planted Royal Gala trees on dwarfing rootstock were used as the experimental materials in 2019—2020 in Alar, southern Xinjiang. Five irrigation volumes were set: W₁ (13.5 mm), W₂ (18 mm), W₃ (22.5 mm), W₄ (27 mm) and W₅ (31.5 mm). ET_0-P was used to guide irrigation. Irrigation was triggered at the same time in the five irrigation treatments when ET_0-P reached 22.5 mm. The study examined the influences of different irrigation volumes on apple growth, water consumption during growth period, yield and water use efficiency, and to provide reference for the large-scale production of apples on dwarfing rootstocks in densely planted orchards in southern Xinjiang. 【Results】New shoots grew rapidly initially and but slowly later, and the length of new shoots increased significantly with the increase in irrigation volume. There was a significant difference in water consumption between different irrigation treatments ($p < 0.05$). The W₁ treatment had the lowest water consumption, which was 304.21 mm and 349.01 mm in 2019 and 2020, respectively, and the W₅ treatment had the highest water consumption, which

收稿日期:2020-11-18 接受日期:2021-01-15

基金项目:兵团节水灌溉试验计划项目(BTJSSY-201806); 基于农业水价改革的田间节水增效关键技术研究与应用(2018AB027); 塔里木大学研究生科研创新项目(TDGRI201926)

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was 692.28 mm and 746.94 mm in 2019 and 2020, respectively. Water consumption rate increased first and then decreased during the growth period. It reached the highest value during the fruit expansion period. The water consumption in W_5 treatment reached 511.72–542.89 mm in fruit expansion period, followed by the fruit maturity period, which was 119.68–131.45 mm, and the lowest in flowering and fruit-setting period, which was 60.88–72.60 mm. The variations in water consumption modulus coefficient and water consumption intensity were consistent with water consumption. In 2019 and 2020, the water consumption modulus and water consumption intensity during fruit expansion period in W_5 treatment were 0.73–0.74 and 6.73–7.24 $\text{mm} \cdot \text{d}^{-1}$, respectively, and the water consumption modulus coefficient and water consumption intensity during the fruit setting period were 0.09–0.10 and 4.54–4.68 $\text{mm} \cdot \text{d}^{-1}$, respectively. The crop coefficient increased with the increase in irrigation volume, and the crop coefficient during the whole growth period was the largest in W_5 treatment and lowest in W_1 treatment in both seasons. Crop coefficient showed a single-peak curve during the whole growth period, peaking in the fruit expansion period. The value in W_5 treatment was 1.36 and 1.49 while that in W_1 treatment was 0.59 and 0.68 in 2019 and 2020, respectively. Apple yield increased first and then decreased with the increase in irrigation volume. The yield in W_4 treatment was the largest, which was 26 960 $\text{kg} \cdot \text{hm}^{-2}$ and 35 328 $\text{kg} \cdot \text{hm}^{-2}$ in 2019 and 2020, respectively, not significantly different from W_3 treatment, but significantly higher than the other treatments. The water use efficiency in W_1 and W_3 treatments was larger, and the two-year average values were 6.59 $\text{kg} \cdot \text{m}^{-3}$ and 6.46 $\text{kg} \cdot \text{m}^{-3}$, respectively. There was no significant difference in water use efficiency among W_1 , W_2 , W_3 and W_4 treatments in 2019, but they were significantly higher than W_5 treatment. The result in 2020 was consistent with that in 2019, but there were significant differences among the treatments. Irrigation water use efficiency displayed a similar pattern with water use efficiency. However, in 2019, there was no significant difference between W_1 and W_3 treatments, and between W_2 and W_4 treatments, and in 2020, there was significant difference between W_2 and W_4 treatments. At the same time, it could be seen from the regression that the correlation coefficients between the average value of output in each treatment, water use efficiency, and irrigation water use efficiency and the irrigation volume in 2019 and 2020 were 0.80, 0.66, and 0.70, respectively, and both water use efficiency and irrigation water use efficiency decreased with the increase in irrigation volume. The fitting curve of irrigation water use efficiency, water use efficiency, yield and irrigation volume correspond to an irrigation volume of about 460 mm. 【Conclusion】Comprehensive analysis of apple growth, water consumption, yield and water use efficiency showed that the irrigation volume during the growth period was 22.5 mm, and the irrigation frequency was 21 times, which was a suitable irrigation mode for dense apple planted on dwarfing rootstocks in South Xinjiang.

Key words: Apple; Close planting of short stock; Water consumption; Yield; Water use efficiency

矮砧密植这一新的种植模式,早果性突出,有利于机械化操作,使得劳动强度大大减轻^[1]。2016年全国矮砧苹果种植面积为 $5.07 \times 10^5 \text{ hm}^2$,占苹果种植总面积的20%,相比于2012年矮砧苹果种植面积增加了 $2.85 \times 10^5 \text{ hm}^2$ ^[2];其中,新疆阿克苏地区的矮砧苹果面积达 928 hm^2 ^[3]。目前,新疆地区农业用水比例超过90%,加剧了与生活及工业用水的矛盾,同时,粗放型灌溉使得灌溉水利用效率及灌溉效益较低。因此,研究矮砧密植苹果灌溉制度,对提高水分

利用效率、增加果农收益及对新疆林果业的发展具有重要意义。

水分是果树生长不可或缺的重要因素,过低的土壤水分不仅会影响果树生长^[4],还对果树叶片光合作用^[5]、产量^[6]及品质^[7]等方面产生显著影响。有研究表明,低灌溉量抑制新梢长度的生长且过高的灌溉量对于新梢长度的生长无显著作用^[8],且新梢长度生长随水分亏缺时间的延长被抑制的愈加明显^[9]。除此之外,耗水特性对灌溉量的响应较大,果

树耗水量不仅取决于所在区域、土壤类型^[10]、生长期^[11],还取决于土壤水分含量及灌溉量。研究表明,耗水量随着灌水定额增大而增大^[12],并随着生育期的推进呈先增后减趋势^[13]。另外,耗水量在不同地区的差异较大。同时,气候较湿润的地区,果树蒸腾耗水主要集中于5—6月,占到全年蒸腾量的37.11%^[14],而在气候干旱区,果树耗水主要集中在7月,占全生育期的30%左右^[15]。耗水量从侧面可反映灌溉定额的多少,但最终以产量、品质及水分利用效率共同反映灌溉定额的适宜性。有研究指出,产量随灌溉定额增加呈先增后减趋势^[16],并在灌溉定额为162 mm时产量最高^[17],而李昭楠等^[18]研究则表明,产量和水分利用效率均随灌溉定额的增加呈先增后减的趋势。

国内学者对果树耗水、产量等方面^[19-20]的研究较多,但针对矮化自根砧苹果的研究较少,尤其是对南疆这种日照强烈、蒸发剧烈及降雨稀少地区的苹果研究更少。苹果作为耗水量较大的果树,对水分的需求较为严格,目前,阿克苏地区苹果以漫灌方式进行灌溉的果园较多,水分利用效率较低,需要制定合理的灌溉措施以提高水分利用效率。因此,笔者通过设置不同的灌水定额,研究苹果树生长、耗水、产量及水分利用效率对灌水量的响应,为南疆地区矮砧密植苹果高效灌溉技术提供支撑,以促进南疆地区苹果优质高产。

1 材料和方法

1.1 研究区域概况

试验于2019—2020年4—8月在新疆生产建设兵团第一师阿拉尔市十团矮砧千亩果园(北纬40°39'14",东经81°16'21")内进行。试验地所在区域属于典型的内陆极端干旱气候区,年均降雨量约为50 mm,年均气温约为11 °C,全年蒸发量为2100 mm左右,全年日照时数约为2900 h,无霜期在200 d以上,地下水埋深约3.0 m。试验地土壤为壤砂土,0~120 cm土层田间持水量为18.5%(体积含水率),平均容重为1.51 g·cm⁻³,有机质含量(w,后同)11.05 g·kg⁻¹,有效磷和有效硼含量分别为3.2 mg·kg⁻¹、0.6 mg·kg⁻¹,速效钾含量为33 mg·kg⁻¹,碱解氮和全氮含量分别为10 mg·kg⁻¹和176 mg·kg⁻¹,铵态氮和硝态氮含量分别为2.01 mg·kg⁻¹和1 mg·kg⁻¹,pH值为8.71,电导率(EC)为154.6 μs·cm⁻¹。

1.2 试验设计

试验采用单因素完全随机设计,设5个灌水定额(W₁: 13.5 mm、W₂: 18 mm、W₃: 22.5 mm、W₄: 27 mm、W₅: 31.5 mm),每个处理3次重复,共15个小区,每个小区内有10株果树,面积为35 m²,同一处理小区之间以授粉树进行隔离。灌水频率根据ET₀-P(参考作物蒸发蒸腾量-降雨量)累积值确定,当ET₀-P达到(22.5±3) mm时进行灌溉。试验于4月22日开始,8月份结束(2019年8月10日结束,2020年8月12日结束),共灌水21次,收获后,灌溉及管理模式与果园保持一致。灌溉定额分别为283.5、378、472.5、567和661.5 mm。

供试材料为5年生皇家嘎拉,果树行株距为3.5 m×1 m(图1)。灌溉水源为渠水,采用水表控制水量且使用滴灌管进行灌水,滴灌管固定在距地面50 cm处的竹竿上,滴头间距30 cm,滴头流量4 L·h⁻¹。采用压差式施肥罐随水施肥,每隔2次灌水施肥1次。施肥及其他农田措施参照当地常规管理。

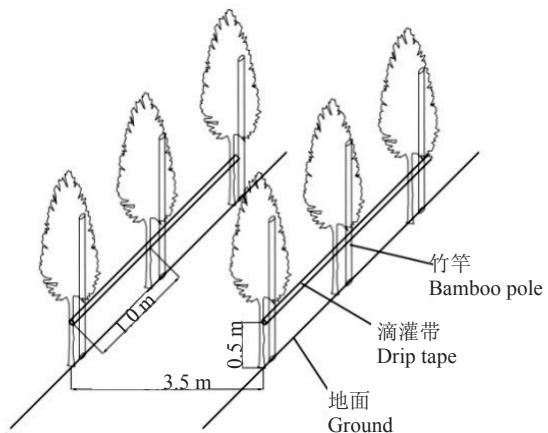


图1 种植模式与滴灌带布置

Fig. 1 Planting mode and layout of drip lines

ET₀通过FAO-56推荐的Penman-Monteith公式计算:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} v_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34v_2)} \quad (1)$$

式中:ET₀为参考作物蒸发蒸腾量(mm·d⁻¹);R_n为净辐射量(MJ·m⁻²·d⁻¹);G为土壤热通量(MJ·m⁻²·d⁻¹);γ为湿度计常数(kPa·°C⁻¹);T为日均气温(°C);v₂为离地面2 m高处的风速(m·s⁻¹);e_s为饱和水汽压(kPa);e_a为实际水汽压(kPa);Δ为温度-饱和水汽

压关系曲线的T处的切线斜率($\text{kPa} \cdot ^\circ\text{C}^{-1}$)。计算 ET_0 的气象数据用HOBO小型气象站获取。

1.3 观测项目与方法

1.3.1 新梢长度 在果树开花坐果期使用直尺对新梢长度进行测量。在树体东西方向选择正常生长的新梢每隔10 d测定1次。2019年从4月21日开始测量,7月30日结束,共测9次。2020年从4月28日开始测量,8月12日结束,共测10次。

1.3.2 土壤含水率及耗水量 土壤含水率采用土壤水分自动监测系统(水分自动监测系统为HOBO,每小时记录1次数据)测定,实时监测0~120 cm土层水分变化,监测点埋设在滴灌带下方,埋设深度分别为20、40、60、80、100、120 cm。同时,在生育阶段始末取土对仪器测定的数据进行标定校准。使用水量平衡法计算生育期耗水量 ET ,计算公式为:

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

式中, ET 为苹果生育期田间耗水量(mm), γ_i 为第*i*层土壤容重($\text{g} \cdot \text{cm}^{-3}$); H_i 为第*i*层土壤厚度(mm); W_{i1} 为第*i*层在时段初始含水率(干土质量的百分率); W_{i2} 为第*i*层在时段末的含水率(干土质量的百分率); M 为各生育期的灌水量(mm); P 为各生育期的降雨量(mm)。

$$R_i/\% = ET/ET \times 100 \quad (3)$$

式中, R_i 为耗水模系数, ET_i 为各生育期的耗水量(mm), ET 为全生育期的耗水量(mm)。

$$Kc = ET/ET_0^{[13]} \quad (4)$$

式中, Kc 为作物系数, ET_i 是各生育期的耗水量(mm), ET_0 为参考作物蒸发蒸腾量(mm)。

1.3.3 产量 于果实成熟期在每个处理选取具有代表性的9株果树进行全部采摘、称重,统计单株果数、单株产量和单果质量,计算各个处理的产量。

1.3.4 水分利用效率和灌溉水利用效率 计算公式为:

$$WUE = Y/ET \quad (5)$$

$$IWUE = Y/I \quad (6)$$

式中, WUE 为水分利用效率($\text{kg} \cdot \text{m}^{-3}$), Y 为苹果产量($\text{kg} \cdot \text{hm}^{-2}$), ET 为果树全生育期耗水量($\text{m}^3 \cdot \text{hm}^{-2}$); $IWUE$ 为灌溉水利用效率($\text{kg} \cdot \text{m}^{-3}$), I 为全生育期灌水量($\text{m}^3 \cdot \text{hm}^{-2}$)。

1.3.5 气象数据 利用HOBO自动气象站监测试验期间气温、太阳辐射、相对湿度、风速、日照时数等

气象指标,降雨量人工测定。

1.4 数据处理与分析

试验数据采用Excel 2010进行整理,利用Origin 2018软件作图并使用DPS v13.5软件进行统计分析,采用Duncan新复极差法进行方差分析和差异显著性检验($\alpha=0.05$)。

2 结果与分析

2.1 气象因子分析

2019—2020年气象因子如图2所示。4—8月,两年 ET_0 均值分别为4.79和4.75 $\text{mm} \cdot \text{d}^{-1}$;风速分别为1.17和0.82 $\text{m} \cdot \text{s}^{-1}$;平均温度分别为23.20和23.23 $^\circ\text{C}$;降雨量分别为30.4和15.4 mm,相差较大。2019—2020年各生育期 ET_0 均值相差较小,果实膨大期和果成熟期较大,开花坐果期最小,分别为4.01和4.09 $\text{mm} \cdot \text{d}^{-1}$;风速则随生育期推进呈下降趋势,开花坐果期最大,分别为1.75和0.9 $\text{m} \cdot \text{s}^{-1}$,果实成熟期最小,分别为0.66和0.74 $\text{m} \cdot \text{s}^{-1}$;日均温则随生育期的推进呈增大趋势,开花坐果期平均温度最低,分别为18.42和20.15 $^\circ\text{C}$,果实成熟期平均温度最高,分别为25.47和26.41 $^\circ\text{C}$;降雨量在果实膨大期最大,分别为22和9.4 mm,且降雨量2019年远高于2020年。

2.2 不同灌水定额对苹果新梢生长的影响

图3为不同灌水处理下苹果新梢长度的变化曲线。新梢长度随灌水量的增加呈增加趋势,即 W_5 处理> W_4 处理> W_3 处理> W_2 处理> W_1 处理,同时,新梢长度随时间推移呈增加趋势,前期各处理新梢生长较快,后期 W_2 和 W_1 处理生长速度明显降低,其他处理新梢生长速度较快。此外, W_5 处理、 W_4 处理、 W_3 处理及 W_2 处理新梢长度在果实成熟期较 W_1 处理分别增加33.20%~49.22%、21.19%~29.76%、13.25%~17.45%和4.66%~6.43%。对新梢长度进行方差分析可知,2019年各处理新梢长度呈显著差异,2020年 W_5 处理、 W_4 处理、 W_3 处理新梢长度显著大于 W_2 和 W_1 处理,但 W_2 和 W_1 处理新梢长度无显著差异。

2.3 不同灌水定额对苹果耗水特性的影响

作物耗水量是农田水分平衡的重要组成部分,是明确土壤水分状况和制定灌溉制度的重要依据,受灌溉方式、作物生长情况及外界环境等因素的影响。由表1可知,各处理全生育期耗水量有显著差

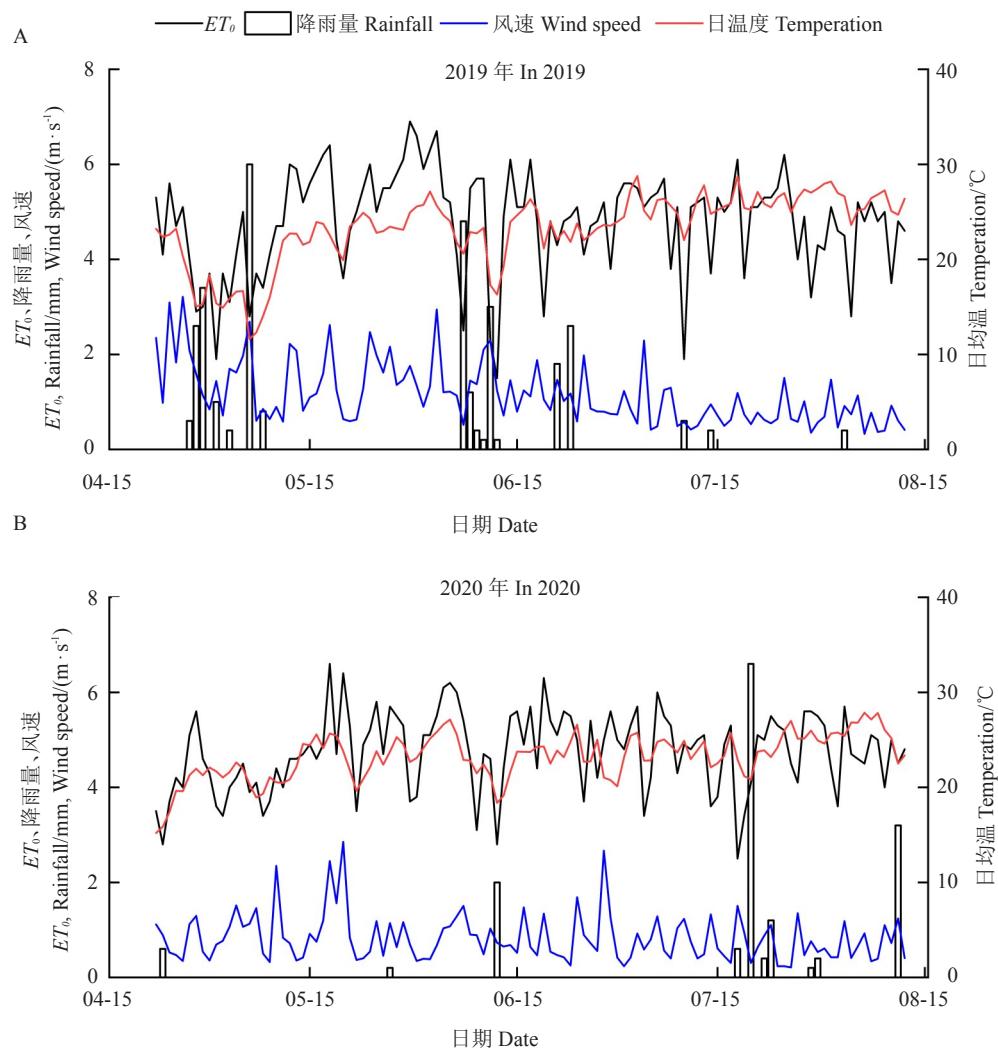


图 2 2019—2020 年气象因子变化
Fig. 2 Variations in meteorological factors in 2019 and 2020

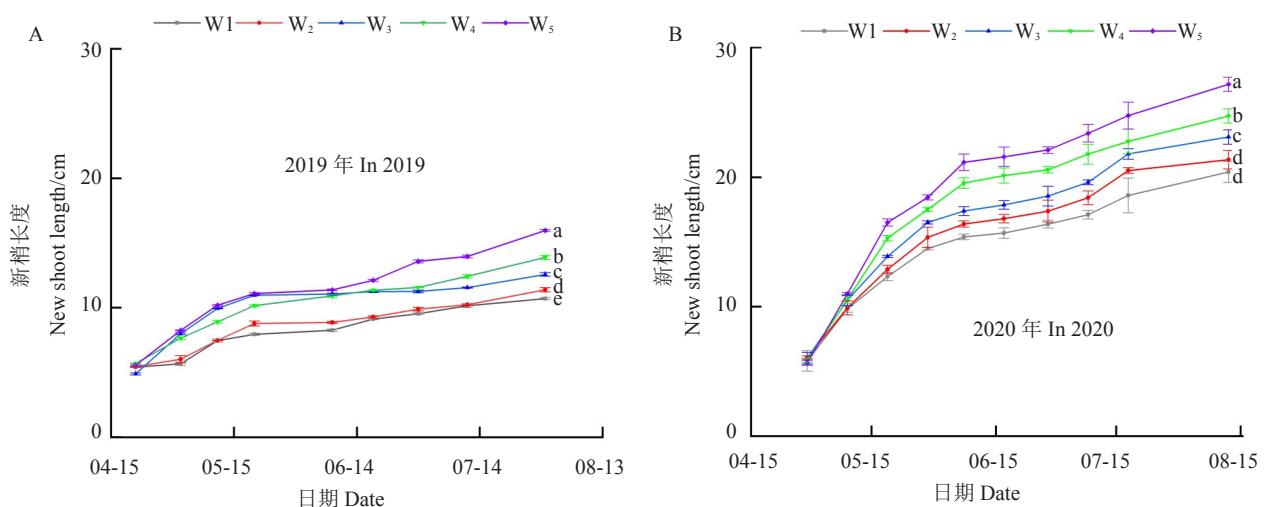


图 3 不同灌水定额对新梢生长的影响
Fig. 3 Effects of different irrigation volumes on new shoot growth

表1 不同灌水定额对苹果耗水特性的影响

Table 1 Effects of different irrigation volumes on apple tree water consumption

年份 Year	处理 Treatment	开花坐果期 Flowering and fruiting period			果实膨大期 Fruit expansion period			果实成熟期 Fruit maturity			总耗水量 Total water consumption/mm
		CA/mm	CP/%	CD/mm	CA/mm	CP/%	CD/mm	CA/mm	CP/%	CD/mm	
2019	W ₁	27.14 e	0.09 b	2.09 e	222.89 e	0.73 b	2.93 e	54.18 e	0.18 a	2.58 e	304.21 e
	W ₂	37.07 d	0.09 b	2.85 d	289.50 d	0.73 b	3.81 d	71.09 d	0.18 a	3.39 d	397.66 d
	W ₃	45.76 c	0.09 b	3.52 c	359.64 c	0.73 b	4.73 c	89.44 c	0.18 a	4.26 c	494.84 c
	W ₄	57.39 b	0.10 a	4.41 b	433.75 b	0.73 b	5.71 b	102.50 b	0.17 b	4.88 b	593.64 b
	W ₅	60.88 a	0.09 b	4.68 a	511.72 a	0.74 a	6.73 a	119.68 a	0.17 b	5.70 a	692.28 a
2020	W ₁	34.88 e	0.10 a	2.18 e	245.74 e	0.70 b	3.28 e	68.38 e	0.20 a	3.11 e	349.01 e
	W ₂	43.70 d	0.10 a	2.73 d	321.82 d	0.71 ab	4.29 d	85.36 d	0.19 ab	3.88 d	450.88 d
	W ₃	52.19 c	0.10 a	3.26 c	396.10 c	0.72 a	5.28 c	99.94 c	0.18 bc	4.54 c	548.23 c
	W ₄	64.21 b	0.10 a	4.01 b	469.92 b	0.72 a	6.27 b	118.00 b	0.18 c	5.36 b	652.13 b
	W ₅	72.60 a	0.10 a	4.54 a	542.89 a	0.73 a	7.24 a	131.45 a	0.18 c	5.97 a	746.94 a

注:CA 为耗水量,CP 为耗水模系数,CD 为耗水强度^[10]。同列不同小写字母表示 0.05 差异水平。下同。

Note: CA is water consumption, CP is water consumption modulus coefficient, CD is water consumption intensity^[10]. The different small letters in the same column indicate significant at 0.05 level. The same below.

异,且随灌水量的增加呈增大趋势,以 W₅ 处理耗水量最大,2019 年和 2020 年耗水量分别为 692.28 和 746.94 mm,W₄ 处理次之,分别为 593.64、652.13 mm,W₁ 处理最小,分别为 304.21 和 349.00 mm。另外,各处理耗水量、耗水模系数及耗水强度均随生育期推进呈先上升后下降的趋势,从大到小依次为果实膨大期、果实成熟期、开花坐果期,说明耗水主要集中于果实膨大期,占全生育期的 70%~74%,日耗水强度相差较大,在 2.93~7.24 mm·d⁻¹ 之间浮动。

2.4 不同灌水定额对苹果生育期 K_c 值的影响

根据 FAO-56 推荐的单作物系数法求得的作物

系数,如表 2 所示。2019—2020 年全生育期及各个生育期的作物系数均呈显著相关,且随灌水量的增加而增大,即 W₅ 处理>W₄ 处理>W₃ 处理>W₂ 处理>W₁ 处理。另外,不同灌水处理作物系数均随生育期的推进呈先上升后下降的趋势,果实膨大期作物系数最大,为 0.59~1.49,果实成熟期略有下降,为 0.55~1.22,开花坐果期最小,为 0.53~1.20。

2.5 不同灌溉定额对苹果产量和水分利用效率的影响

表 3 为 2019—2020 年不同灌水量下产量构成因子及水分利用效率。苹果产量构成因子均随灌水量的增加呈先增加后减小的趋势,均在 W₄ 水分处理下

表2 不同灌水定额对苹果作物系数的影响

Table 2 Effect of different irrigation volumes on apple crop coefficient

年份 Year	处理 Treatment	开花坐果期 Flowering and fruiting period		果实膨大期 Fruit expansion period		果实成熟期 Fruit maturity		全生育期 Full growth period	
		ET ₀ /mm	K _c	ET ₀ /mm	K _c	ET ₀ /mm	K _c	ET ₀ /mm	K _c
2019	W ₁	50.9	0.53 e	377.1	0.59 e	98.7	0.55 e	526.7	0.58 e
	W ₂		0.73 d		0.77 d		0.72 d		0.75 d
	W ₃		0.90 c		0.95 c		0.91 c		0.94 c
	W ₄		1.13 b		1.15 b		1.04 b		1.13 b
	W ₅		1.20 a		1.36 a		1.21 a		1.31 a
2020	W ₁	65.5	0.53 e	363.4	0.68 e	107.5	0.64 e	536.4	0.65 e
	W ₂		0.67 d		0.89 d		0.79 d		0.84 d
	W ₃		0.80 c		1.09 c		0.93 c		1.02 b
	W ₄		0.98 b		1.29 b		1.10 b		1.22 c
	W ₅		1.11 a		1.49 a		1.22 a		1.39 a

表3 不同灌溉定额对苹果产量和水分利用效率的影响

Table 3 Effects of different irrigation volumes on apple yield and water use efficiency

年份 Year	处理 Treatment	株产 Yield per plant/kg	单株果数 Number of fruits per plant	单果质量 Single fruit weight/g	产量 Yield/(kg·hm ⁻²)	WUE/ (kg·m ⁻³)	IWUE/ (kg·m ⁻³)
2019	W ₁	5.72 d	53.00 b	108.47 c	16 480.00 d	5.42 a	5.81 a
	W ₂	6.38 c	54.33 b	116.77 bc	18 384.00 c	4.62 a	4.86 b
	W ₃	9.16 a	72.44 a	126.96 ab	26 377.60 a	5.33 a	5.58 ab
	W ₄	9.36 a	71.67 a	134.97 a	26 960.00 a	4.54 a	4.75 b
	W ₅	8.56 b	68.00 a	126.63 ab	24 659.20 b	3.56 b	3.73 c
2020	W ₁	7.24 c	70.67 b	102.54 b	20 856.00 c	5.98 b	7.36 a
	W ₂	7.69 c	72.50 b	106.20 b	22 152.00 c	4.91 d	5.86 c
	W ₃	12.05 a	101.00 a	119.62 a	34 704.00 a	6.33 a	7.34 a
	W ₄	12.27 a	98.83 a	124.12 a	35 328.00 a	5.42 c	6.23 b
	W ₅	9.82 b	94.17 a	104.67 b	28 272.00 b	3.79 e	4.27 d

达到最大值,且2020年单株产量、单株果数均高(多)于2019年,单果质量却相反。苹果产量随灌水量及耗水量的变化趋势与产量构成因子相同,其中,W₄处理苹果产量最高,与W₃处理无显著差异,但W₄和W₃处理产量较其他处理差异显著。2019年,WUE以W₁处理和W₃处理较大,与W₂和W₄处理无显著差异,但显著高于W₅处理,IWUE的变化规律与WUE相似,W₁处理和W₃处理与W₂处理和W₄处理无显著差异,显著高于W₅处理;2020年,W₁处理和W₃处理的WUE分别为5.98和6.33 kg·m⁻³,两处理间及其他处理差异显著,IWUE则以W₁和W₃处理较

大,分别为7.36和7.34 kg·m⁻³,无显著差异性,但显著高于其他处理。

产量、WUE及IWUE与灌溉定额之间的关系如图4所示。2019—2020年产量、WUE和IWUE均值与灌水量呈二次曲线关系,相关系数R²分别为0.80、0.66和0.70,且WUE和IWUE随灌水量增加呈减小趋势。由图4可知,当苹果产量达到29 695.91 kg·hm⁻²时,灌水量为5 513.92 m³·hm⁻²;当WUE达到5.56 kg·hm⁻²时,灌水量为3 773.38 m³·hm⁻²;当IWUE为6.29 kg·m⁻³时,灌水量为3 444.19 kg·m⁻³。同时,产量、WUE及IWUE与灌水量拟合曲线交点区间对应的灌水量为

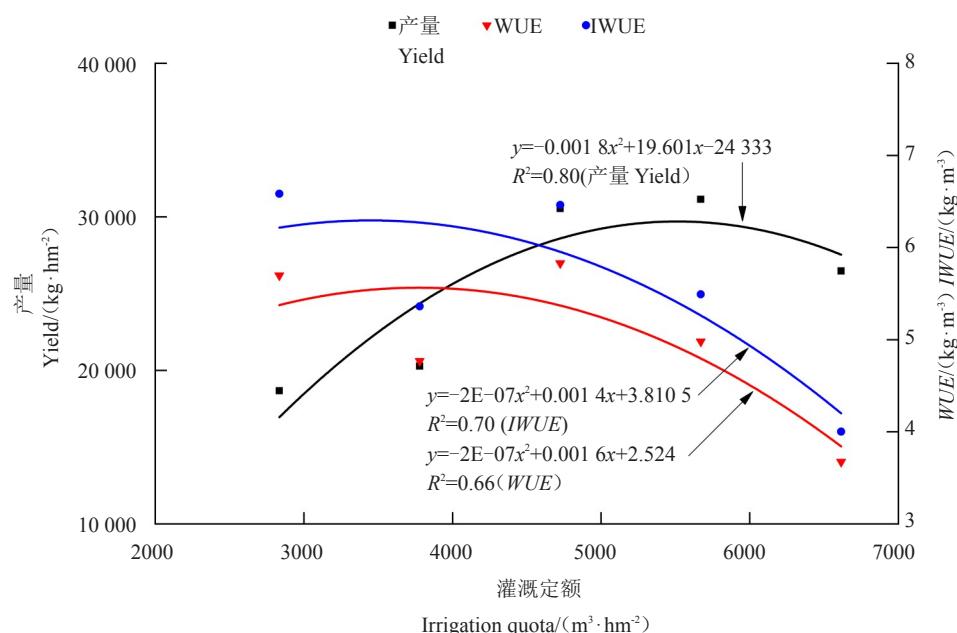


图4 产量、WUE及IWUE与灌溉定额的关系

Fig. 4 Relationships between yield, WUE, IWUE and irrigation volume

4000~5000 m³·hm⁻²。

3 讨 论

苹果树比一般作物高大,根系发达,耗水量远高于一般作物且各生育期耗水不尽相同,因而对苹果生长、耗水特性及产量的研究尤为重要。笔者研究表明,灌水量增加对新梢生长具有显著影响($p < 0.05$)且低灌水量对新梢长度具有明显抑制作用。赵瑞芬等^[21]和单长卷等^[22]研究发现,新梢长度随灌水量增加而增大,这与本文研究一致,可能是水分过少导致光合产物在树体不同器官中的分配不同^[20,23]。另外,新梢长度前期增长较快,后期增长变缓,原因可能是前期果实较小,树体营养器官优先发育,而后期果实进入快速膨大期和成熟期后,光合产物供给多倾向于生殖器官果实^[24-25]。

作物耗水量是制定灌溉制度的前提,开展作物耗水规律研究,可以确定苹果的水分消耗能力以及适应干旱环境的能力^[26]。本研究表明,苹果耗水量随灌水量增加而增加,这与赵建国等^[27]的研究结果相同,与漫灌相比,滴灌条件的耗水量降低27.39%~56.48%,说明滴灌可有效减小土壤蒸发,有利于果树对水分吸收^[28]。本研究表明,不同水分处理下,果树耗水随生育期变化呈先上升后下降的趋势,果实膨大期耗水量最大,成熟期次之,开花坐果期最小,这与党宏忠^[29]在黄土高原地区的研究结果类似,可能是果树在果实膨大期生理活动最活跃,且持续时间最长,而开花坐果期持续时间短,加上此期苹果叶片较小,果树生理耗水量最小。研究发现,耗水强度在生育期内呈单峰型,表现为果实膨大期最大,果实成熟期次之,开花坐果期最小,原因可能是果实膨大期环境温度较高,潜在蒸发剧烈,并且果树叶片发育良好,进而耗水强度最大,而开花坐果期最小,原因是此时期温度低、耗水量小;其次,耗水模系数在各生育期相差不大,且在果实膨大期最大,这与党宏忠等^[29]和李晶等^[30]的研究类似。

作物系数是确定作物耗水量的基础^[31],是制定适宜灌溉制度的依据^[13],对农田水分平衡及水资源利用有重大意义^[32],综合反映作物本身的生物学特性、田间管理措施、土壤水肥等多方因素对耗水量的影响^[33]。全国栋等^[34]研究表明,核桃作物系数随生育期的推进呈先上升后下降的趋势,同时,邱让建等^[35]研究得出,番茄的作物系数呈先上升后下降的

趋势。另外,胡永翔等^[13]通过研究发现,枣树的作物系数在果实膨大期最大。本试验研究发现,苹果作物系数随生育期的推进呈先上升后下降的趋势,并在果实膨大期最大,这与曾建^[36]的研究结果一致,可能是耗水量和参考作物蒸发蒸腾量均达到较高值^[12]。

本研究发现,灌水量对产量影响显著,苹果产量随灌水量的增加呈先增后减趋势,这与晏清洪等^[16,37-38]的研究类似,原因可能是适宜灌水量可抑制新梢旺长,有利于果实膨大以及减少落果。水分利用效率和灌溉水利用效率则随灌水量增加呈现先降低后增加再降低的趋势,这与龚雪文等^[39]和张鹏等^[40]的研究结果不同,原因主要是W₁和W₂与W₂和W₃处理间产量增幅与耗水量及灌水量增幅相差较大,但从拟合情况来看,水分利用效率随灌水量增大而减小,灌溉水利用效率与水分利用效率规律一致。与地面灌溉相比,滴灌可以增产22%,同时,灌溉水利用率提高240%^[41],说明滴灌条件更有利于果树生长。

4 结 论

新梢长度随灌水量的增加而增加,且随时间推移呈递增趋势;耗水量则随灌水量的增加而增大,且生育期中以果实膨大期耗水量最大,占总耗水的70%~74%,耗水强度和Kc的变化规律与耗水量一致;W₃处理产量较高且与W4处理无显著差异,WUE和IWUE随灌水量增加呈递减趋势。因此,适宜南疆矮砧密植苹果生长的灌溉定额为472.5 mm。

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