覆膜耕作方式对河套灌区土壤水热效应及玉米产量的影响

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摘 要：通过设置垄作全膜、垄作半膜、平作全膜以及平作半膜 4 个覆膜耕作处理，探究不同覆膜耕作方式对河套灌区土壤水热及春玉米产量的影响。结果表明：1）2 个生长季内垄作全膜处理各阶段土壤含水率和温度均最高，保水保温效果明显。2）耕层土壤温度的变化规律和含水率的变化规律相反，随着土壤温度升高，土壤含水率逐渐降低。3）玉米生育期内随着温度升高和作物耗水量增大，全膜覆盖和垄作耕作方式的蓄水保墒效果愈加明显；干旱条件下，耕作措施较覆膜方式对地温的影响更为明显；而在水量充沛条件下，覆膜方式则表现出对地温更显著的影响。田间起垄耕作结合全膜覆盖的种植方式，可以获得较高的穗行数和穗粒数，有利于干物质的积累，促进滴灌条件下玉米产量的形成，同时提高水分利用效率，为河套灌区农业节水和玉米高产提供了技术依据。

关键词：灌溉；土壤；水分；滴灌；耕作方式；覆膜；土温；玉米
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0 引 言

河套灌区是中国重要的粮油生产基地，灌区光热资源丰富，气候干旱少雨，夏季高温干热，蒸发强烈，气温变化幅度大，极易造成作物减产[1-3]，因而探索适宜灌区作物生长的良好水热环境成为一项重要的研究课题。膜下滴灌是将滴灌与覆膜技术相结合的一种灌溉方式[4]，研究表明，覆盖地膜能够改善土壤水热条件，降低土壤水分的无效蒸发和热量散失，提高作物产量[5-9]。垄作和地膜覆盖相结合，具有促进作物生长、增温保墒，提高作物水分利用率的作用[10-14]。龚雪文等[15]通过试验证明河套灌区套种农田膜下滴灌有利于作物根区形成良好的水热环境，促进作物生长。马树庆等[16]研究表明，通过地膜覆盖，可以提高田间土壤温度，将玉米生育期提前，提高光合产物积累。张俊鹏等[17]基于大田对比试验发现秸秆和地膜覆盖增加了夏玉米干物质量，提高了水分利用效率。马忠明等[18]对旱地砂田不同覆膜栽培模式的土壤水热效果和增产效果进行研究，结果表明，起垄覆膜较无膜对照处理 0～25 cm 土层土壤日平均温度提高 2.0 ℃，起垄覆膜具有明显的集雨保墒效果，是旱砂田优选的覆膜方式。

本文结合河套灌区农业耕作措施发展特点，采用膜下滴灌技术，通过设置不同耕作措施和覆膜方式组合，主要研究作物不同生育时期膜下不同位置土壤水热变化规律，分析不同覆膜方式下滴灌对土壤水热运移的影响，明确不同耕作覆膜措施的水热效应及玉米产量性状差异，为改善干旱灌区农田土壤水热条件、提高灌水利用效率和玉米产量、保障作物健康生长提供技术方法和理论依据。

1 材料与方法

1.1 试验区概况

田间试验位于河套灌区的曙光试验站（40°46″N，107°24″E），海拔高度 1 039 m，地处干旱半干旱气候带，属典型的温带大陆性气候，降水集中，全年日照充足，蒸发强烈，空气干燥，昼夜温差差较大。试验站多年平均气温 6.9 ℃，降雨量 142.1 mm，蒸发量 2 306.5 mm。无霜期 160 d，年日照时数 3 189 h。试区内土壤属于黄河灌淤土，质地主要为沙壤土，耕层平均土壤容重 1.40 g/cm^3，土壤有机质质量分数 7.26 g/kg，全氮质量分数 105.36 mg/kg，速效磷质量分数 55.82 mg/kg，速效钾质量分数 120.49 mg/kg，土壤盐分质量分数 1.19 g/kg，地下水埋深 2.5 m 左右。0～120 cm 土壤田间持水量 23.85%，土壤容重 1.49 g/cm^3。

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1.2　试验设计

试验于 2014－2015 年进行，供试作物为玉米。在膜下滴灌条件下，设置 2 种地膜覆盖方式（半膜、全膜）和 2 种耕作措施（平作、垄作），共 4 个处理，分别为垄作全膜（LQ）、垄作半膜（LB）、平作全膜（PQ）和平作半膜（PB）。每个处理 4 个重复，共计 16 个小区，小区面积 4 m×12 m。各处理均采用宽窄行的种植方式，窄行和宽行行距分别为 20 和 80 cm，在窄行中间布置滴灌带，滴灌带间距 100 cm，滴头间距 30 cm，玉米株距 30 cm。垄作处理垄高 20 cm，垄宽 40 cm，垄间距 100 cm。

供试玉米品种为西蒙 6 号，地膜为高压聚乙烯膜，厚度 8 μm。2014 年播种时间为 4 月 24 日，2015 年为 4 月 28 日，播种前施加底肥（尿素、二胺）并覆盖地膜，播种深度 5 cm，分别于 2014 年 9 月 4 日和 2015 年 9 月 5 日收获。在玉米拔节期和抽雄前追肥，追肥为尿素、磷肥和硝酸钾，将肥料溶于施肥罐中随灌水施入。所有处理施肥量一致，田间管理措施相同。

1.3　测定指标与方法

含水率和温度测定：采用 ECH_2O-5TE（Decagon Devices, Inc., USA）土壤水分、温度动态监测系统实时监测土壤含水率和温度变化。监测从播种前开始到收获后结束，每 1 h 测定 1 次，数据采集仪自动记录。探针埋设在滴头下方，最窄边向上垂直插入土壤，埋设深度为 10、30 和 55 cm。

产量及其构成测定：在收获期取每小区中间 2 行进行测产，记录穗数，收获后随机选择 20 个果穗记录每穗行数，每行粒数，脱粒后称量籽粒鲜质量，50 ℃烘干至恒质量，计算千粒质量。

采用水量平衡法计算玉米耗水量 ET（evapotranspiration，mm）

$$\mathrm{ET}=\Delta W+P+I+G+R+F \tag{1}$$

式中 ΔW 为播种期与收获期土壤储水量之差，mm；P 为生育期有效降雨量，mm，如果降雨量小于当日参考蒸发蒸腾量的 0.2 倍，视为无效降雨[19]；I 为玉米生育期的灌水量，mm；G 为生育期地下水对作物根系的补给量，mm，详细计算过程参考文献[20]；R 为生育期地表径流量，mm，试区地势平坦，无地表径流产生；F 为生育期根区深层渗漏量，mm，根据 FAO56 分册中提供的方法计算，假定降雨或灌溉先补给根系层土壤水分至田间持水量，多余的水分即为深层渗漏损失量[19]。

玉米水分利用效率（water use efficiency，WUE，kg/(hm^2·mm)）计算公式

$$\mathrm{WUE}=\frac{Y}{\mathrm{ET}} \tag{2}$$

式中 Y 为单位面积玉米产量，kg/hm^2。

1.4　数据分析

采用 SigmaPlot12.0 绘制图形，使用 R3.1.0 进行数据处理与统计分析，多重比较基于最小显著差数法（least significant difference，LSD）进行。

2　结果分析

2.1　覆膜耕作方式对土壤含水率的影响

不同覆膜耕作方式土壤含水率变化见表 1。2 个生长季不同生育期覆膜方式对土壤含水率影响较大，玉米苗期和拔节期全膜覆盖处理不同深度土壤含水率均高于半膜覆盖处理。其中，全膜覆盖时，垄作土壤含水率高于平作，大部分时候差异达显著水平（P<0.05）；半膜覆盖时，垄作与平作处理之间差异大多不显著。抽雄期和成熟期 10 和 55 cm 深度土壤含水率在处理间的变化趋势与苗期和拔节期一致，但 30 cm 深度土壤含水率却是半膜覆盖高于全膜覆盖。

表 1　不同覆膜耕作方式下土壤含水率变化

Table 1　Soil moisture in different growing stages under different treatment　%

处理 Treatment		苗期 Seeding stage			拔节期 Jointing stage			抽雄期 Heading stage			成熟期 Maturing stage		
		10 cm	30 cm	55 cm	10 cm	30 cm	55 cm	10 cm	30 cm	55 cm	10 cm	30 cm	55 cm
2014	LQ	17.64a	20.05a	16.07a	18.64a	20.61a	17.79a	18.38a	15.66b	17.20a	17.00a	13.55b	13.58a
	LB	14.47c	16.26c	12.78c	15.34c	17.05c	13.91b	15.08c	18.58a	13.55b	13.68c	16.45a	11.43b
	PQ	16.12b	18.67b	15.14b	16.73b	19.55b	17.00a	16.51b	16.19b	16.74a	15.75b	13.99b	13.10a
	PB	14.79c	17.49c	11.92c	15.62c	17.96c	13.37b	15.34c	17.32a	13.18b	14.25c	15.54a	11.16b
2015	LQ	19.94a	23.79a	15.77a	20.71a	24.53a	16.00a	19.98a	21.24b	12.67a	19.86a	20.55c	11.95a
	LB	17.36c	21.47b	13.32c	17.99c	22.08b	13.70c	18.50b	22.75a	10.06c	16.45c	23.49a	10.23c
	PQ	19.23b	23.19a	14.21b	20.38a	24.01a	15.15b	19.91a	21.47b	11.60b	19.77a	21.36c	10.68b
	PB	18.32c	22.17b	13.93c	19.07b	22.90b	14.24c	18.84b	22.35a	10.22c	18.37b	22.50b	10.32c

注：LQ、LB、PQ 和 PB 分别为垄作全膜、垄作半膜、平作全膜和平作半膜处理；不同字母表示处理间差异显著（P<0.05）；下同。

Note: LQ, LB, PQ and PB indicate ridge tillage with full film mulching, ridge tillage with partial film mulching, flat tillage with full film mulching and flat tillage with partial film mulching, respectively; different letters indicate significant differences between treatments (P<0.05); the same below.

2.2　覆膜耕作方式对土壤温度的影响

地膜覆盖和垄作耕作方式改变了地表的热量平衡，2 个生长季内不同生育期平作半膜土壤温度最低，垄作全膜土壤温度最高，各处理 10 cm 深度土壤温度最高，随着土层深度增加，土壤温度逐渐降低（表 2）。第 1 季各生育期 10、30 和 55 cm 深度垄作处理土壤温度均高于平作，耕作措施较覆膜方式对地温的影响更为明显，垄作处理土壤温度在 13.30～27.03 ℃间变化，平作处理土壤温度在 12.54～25.01 ℃间变化，其中，垄作全膜土壤温度高于垄作半膜，平作全膜土壤温度高于平作半膜。第 2 季各生育期 10、30 和 55 cm 深度土壤温度均为全膜覆盖高于半膜覆盖，覆膜方式较耕作措施对地温的影响更为明显，全膜覆盖处理土壤温度在 13.64～26.47 ℃间变化，半膜覆盖处理土壤温度在 11.97～24.31 ℃间变化，其中，垄作全膜土壤温度高于平作全膜，垄作半膜土壤温度高于平作半膜。

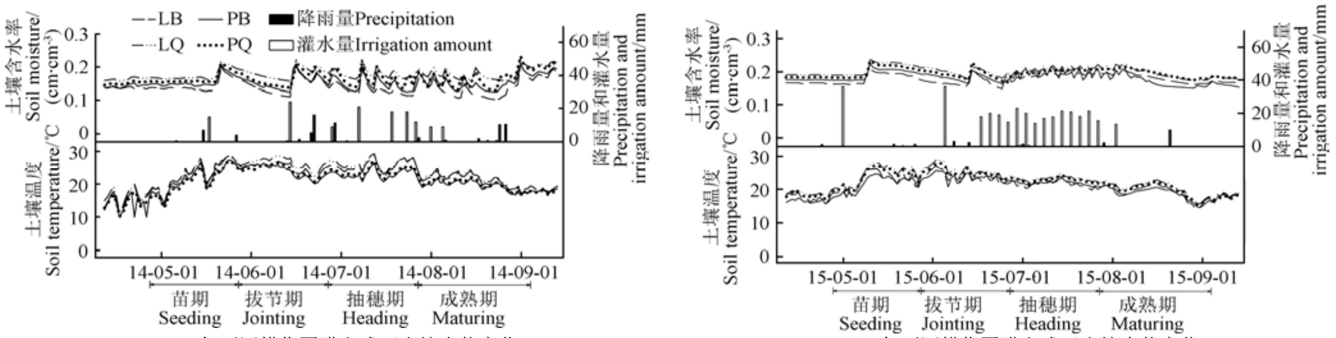
表 2 不同覆膜耕作方式下土壤温度变化

Table 2 Soil temperature in different growing stages under different treatment ℃

处理 Treatment		苗期 Seeding stage			拔节期 Jointing stage			抽雄期 Heading stage			成熟期 Maturing stage		
		10 cm	30 cm	55 cm	10 cm	30 cm	55 cm	10 cm	30 cm	55 cm	10 cm	30 cm	55 cm
2014	LQ	20.02a	16.79a	13.89a	27.03a	24.35a	21.09a	25.72a	24.04a	21.94a	22.78a	22.16a	21.18a
	LB	19.73b	16.47b	13.30b	26.12b	23.55b	20.69b	24.89b	23.94b	21.95a	22.28b	21.98b	20.79b
	PQ	18.15c	15.82c	13.43b	25.01c	23.41b	20.34c	23.35c	23.21c	20.96b	20.91c	21.41c	20.20c
	PB	17.88d	15.76c	12.54c	24.97c	23.20c	19.98d	22.65d	22.08d	20.46c	20.46d	20.52d	19.67d
2015	LQ	19.45a	16.73a	13.66a	26.47a	23.34a	20.36a	24.11a	23.00a	21.31a	22.16a	20.96a	19.93a
	LB	17.99b	16.03c	12.45b	24.31c	22.41b	18.57c	22.74b	22.09c	20.04c	20.97b	20.50b	19.38c
	PQ	19.33a	16.52b	13.64a	25.65b	23.26a	20.06b	23.99a	22.38b	20.61b	22.05a	20.85a	19.83b
	PB	17.16c	15.14d	11.97c	23.46d	21.37c	18.10d	22.41c	21.72d	19.79d	20.52c	20.14c	19.01d

2.3 覆膜耕作方式对耕层土壤水热动态变化的影响

2 个生长季各处理耕层（0～20 cm）土壤含水率随时间动态变化趋势基本相同（图 1），全膜覆盖处理耕层土壤含水率普遍高于半膜覆盖。第 2 季（图 1b）抽雄期高频灌溉，各处理土壤含水率变化范围较小，各处理之间的效果差异不如缺水干旱（图 1a）时明显。图 1 各处理土壤温度随时间动态变化的趋势相同，耕层土壤温度随时间的变化规律与含水率的变化趋势相反，随着土壤温度升高，土壤含水率逐渐降低。



a. 2014 年不同耕作覆膜方式下土壤水热变化

a. Dynamics of soil moisture and temperature under different treatments in 2014

b. 2015 年不同耕作覆膜方式下土壤水热变化

b. Dynamics of soil moisture and temperature under different treatments in 2015

注：LQ、LB、PQ 和 PB 分别为垄作全膜、垄作半膜、平作全膜和平作半膜处理。

Note: LQ, LB, PQ and PB indicate ridge tillage with full film mulching, ridge tillage with partial film mulching, flat tillage with full film mulching and flat tillage with partial film mulching, respectively.

图 1 不同覆膜耕作方式下玉米生育期内耕层土壤含水率与地温变化（2014—2015）

Fig.1 Soil moisture and temperature dynamics in different growth stages under different treatment in 0-20 cm soil layer (2014—2015)

2.4 覆膜耕作方式对玉米产量性状和水分利用效率的影响

不同覆膜耕作方式下玉米产量性状如表 3 所示。2 个生长季穗行数、穗粒数垄作全膜处理最高，垄作半膜处理最低，全膜和半膜处理穗行数差异显著，相同覆盖方式下垄作和平作处理穗行数没有显著差异。覆膜耕作方式对千粒重和存果率的影响较为复杂，2014 年全膜覆盖仍然表现出明显的正效应，2015 年则无明显规律可循。

2 个生长季内全膜和半膜覆盖处理玉米产量差异显著，半膜覆盖产量显著低于全膜覆盖，垄作全膜增产效果最优。与当地“全膜平作+大水漫灌”处理（CK）相比，2 个生长季内垄作全膜和平作全膜处理分别增产 22.22%、11.98%和 30.92%、28.18%，垄作半膜产量减少 16.70%和 8.21%，平作半膜第 1 季产量较 CK 减少 3.18%，第 2 季则增产 2.85%。另外，2 个生长季 CK 耗水量均为最高，分别为 536 和 521 mm。不同覆膜耕作处理对玉米水分利用效率的影响显著，2 个生长季垄作全膜水分利用效率最高，分别为 40.21 和 39.10 kg/(hm^2·mm)，常规耕作 CK 水分利用效率最低，分别为 23.79 和 24.61 kg/(hm^2·mm)。

表 3 不同覆膜耕作方式下玉米产量和水分利用效率对比

Table 3 Comparison of maize yield and water use efficiency in different treatments

年份 Year	处理 Treatment	穗行数 Number of rows per ear	穗粒数 Number of grains per ear	千粒质量 1 000 grain weigh/g	存果率 Rate of fruiting	产量 Yield/(kg·hm^{-2})	耗水量 Water consumption/mm	水分利用效率 Water use efficiency/(kg·(hm^{-2}·mm^{-1}))
2014	CK	—	—	—		12750	536.05	23.79
	LQ	19.14a	692.00a	390.30a	0.95a	15583a	387.5a	40.21a
	LB	16.21b	548.67b	355.08c	0.91b	10925c	351.72c	31.06d
	PQ	18.33a	678.00a	375.07b	0.95a	14277a	363.28b	39.29b
	PB	16.47b	648.33a	333.32d	0.91b	12357b	365.42b	33.83c
2015	CK	—	—	—		12830	521.41	24.61
	LQ	24.72a	980.19a	369.67b	0.87c	16797a	429.32a	39.10a
	LB	21.22b	739.14c	402.72a	0.84d	11857b	394.17c	30.08d
	PQ	23.06a	837.83b	344.47d	0.91a	16445a	412.61b	38.29b
	PB	21.38b	806.84b	338.73c	0.90b	13196b	411.65b	32.06c

3 讨 论

垄作覆膜可以抑蒸保墒，改善作物水分状况[21-22]。垄作处理增厚土壤疏松土层，有效促进土壤水分入渗[23]；同时，垄作可以增加土壤表面积，接收太阳辐射能力增强，致使表层土壤温度更易提高，利于热量向深层土壤传递[24-25]。覆盖地膜后，阳光中的长波辐射反射到近地面的空气中转化为热能，提高作物周围空气温度，而短波辐射部分被地表反射，转化为热能提高膜内温度，另一部分以热传导的方式传递至深层，与半膜覆盖相比，全膜覆盖防止热量从膜间裸地扩散，能有效提高土壤温度[26-28]。

本试验各处理土壤含水率的变化除了受到地膜覆盖和耕作方式的影响外，也受到玉米生长耗水的影响[29]。玉米苗期根系较浅且耗水量少，主要吸收表层土壤水分，对深层土壤含水率影响较小。拔节期地表温度升高，土壤蒸发量增大，半膜处理膜间裸地水分散失，土壤含水率较低，全膜覆盖保水效果较好。抽雄期在第 2 个生长季采用高频灌溉，表层含水率长期维持在较高水平，耕作措施对土壤含水率和温度的影响有限，覆膜方式较耕作措施对地温的影响更为明显。抽雄期 10 和 55 cm 深度全膜覆盖土壤含水率高于半膜覆盖，而 30 cm 深度全膜覆盖土壤含水率明显低于半膜覆盖，分析原因，是由于该时期全膜覆盖作物生长旺盛，长势明显优于半膜覆盖，蒸腾耗水量大，且滴灌单次灌水量 20 mm 左右，主要入渗区域在 0～30 cm 附近，对 55 cm 以下土壤含水率影响较小，灌水供给作物蒸腾耗水，主要入渗区 30 cm 处土壤含水率低于半膜覆盖[11]，而全膜覆盖处理地膜表层水气凝结，10 cm 深度土壤含水率高于半膜覆盖。进入成熟期，玉米根系发达，作物耗水量大且灌水少，土壤水分消耗是影响土壤含水率的重要因素，各处理不同深度土壤含水率变化规律与抽雄期一致。

第 2 季玉米存果率明显低于第 1 季，这是因为第 2 季播期试验区风力较大，土壤水分蒸发强烈，导致土壤墒情较差，对作物前期生长有一定影响，而后期采用高频灌溉一定程度上弥补了前期墒情差的不足，保证了玉米穗粒数、千粒重的提高，从而促使 4 个处理产量较第 1 季均有所提高。垄作全膜处理在不同生育期耕层土壤温度、水分都是最佳的，为玉米生长提供了适宜的耕层土壤水热环境。在玉米生长前期垄作全膜的抑蒸保墒作用起到较好的保水效果，提高了土壤含水率，加速玉米的生育进程，作物生长旺盛，长势明显优于其他处理；同时，垄作全膜促进热量传递和积聚，避免热量散失，提高了土壤温度，且地表昼夜温差较大，有益于干物质的积累和转移，促进作物生长发育和产量的形成，增产效果最明显。

4 结 论

1）垄作全膜覆盖方式大幅提高了土壤含水率，尤其在玉米苗期和拔节期，同时对耕层土壤保温效果明显，干旱条件下，耕作措施较覆膜方式对地温的影响更为明显；而在水量充沛条件下，覆膜方式则表现出对地温更显著的影响。

2）垄作全膜处理提高了玉米产量和水分利用效率，与当地“全膜平作+大水漫灌”处理（CK）相比，2 个生长季内分别增产 22.22%和 30.92%，水分利用效率分别为 40.21 和 39.10 kg/(hm^2·mm)，一定程度上解决了灌区玉米耗水量大、水分利用效率低的问题。

综上所述，垄作全膜覆盖方式在河套地区应用，可以优化耕层土壤水热环境，提高玉米穗行数和穗粒数，利于干物质的积累，促进滴灌条件下的玉米产量形成，同时提高水分利用效率，是适宜于河套灌区的一种高效种植模式。

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Effects of mulch and tillage methods on soil water and temperature as well as corn yield in Hetao irrigation district

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Abstract: Soil hydrothermal condition is one of the most important factors affecting crop growth and development in semi-arid areas. In this study, we aimed to investigate effects of different film and tillage technology modes on spring maize yield and soil hydrothermal condition in Hetao Irrigation District. The experiment included four treatments: ridge tillage with full film mulching (LQ), ridge tillage with partial film mulching (LB), flat tillage with full film mulching (PQ) and flat tillage with partial film mulching (PB). The results showed that the soil moisture and soil temperature of LQ were higher (P<0.05) than the LB, PQ and PB treatments in the whole growing stage in 2014 and 2015. The suitable soil thermal conditions in LQ made plant grow vigorously, and it consumed large amount of soil water to enhance biomass and leaf area accumulation. In addition, the full film mulching was more effective at enhancing component factors influencing yield and reserving water in soil profile than partial film mulching, which resulted in higher yield and water use efficiency (WUE). There was an inverse correlation between soil temperature and soil moisture in arable layer. With the increasing of temperature and crop water consumption during growing period, LQ showed significant effect on soil water conservation. In 2014 and 2015, the soil temperature was higher (P<0.05) in LQ than in other treatments while the lowest value was recorded in the PB treatment. However, the soil temperature in LB was higher (P<0.05) than in PQ in 2014; it was opposite that higher soil temperature was recorded in PQ compared with LB in 2015. It implied that tillage technology had a significant influence on average temperature compared with mulching mode under drought conditions in 2014. Conversely, mulching mode played an more important role in preserving thermal conditions than tillage technology during the humid year in 2015. Overall, ridge tillage efficiently transferred and accumulated heat from shallow soil layer to deeper layers. Additionally, the higher the soil surface temperature, the more significant the film insulation effect. LQ can not only enhance the number of rows per ear and grain number, but also were conducive to the accumulation of dry biomass, promote the formation of maize yield under drip irrigation, and increase water use efficiency. LQ efficiently promoted water infiltration and regulated the surface temperature resulting in soil moisture conservation and evaporation inhibition. These effects were much clearer and more consistent with ridge tillage. In addition, full plastic film mulch had an insulation effect compared with partial plastic film mulch, and thus thermal energy could be effectively transferred and stored at the tillage layer where it was essential for maize growth. This study could provide a theoretical basis for improving soil hydrothermal conditions in Hetao Irrigation District and thus enhance crop productivity and quality.

Keywords: irrigation; soils; water; drip irrigation; tillage methods; film mulch; soil temperature; corn