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Cotton's Water Demand and Water-Saving Benefits under Drip Irrigation with Plastic Film Mulch

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Abstract The primary purpose of this research was to give suitable irrigation program according to the growth period and water requirement.

A cotton field experiment with mulched drip irrigation was conducted at the National Field Observation and Research Station for Oasis Farmland Ecosystem in Aksu of Xinjiang in 2008. Water balance method was adopted to study the water requirement and water consumption law of cotton under mulched drip irrigation in Tarim Irrigated Area. Statistical analysis of experimental data of irrigation indicates that the relationship between yield of cotton and irrigation presents a quadratic parabola. We fit the model of cotton water production on the basis of field experimental data of cotton. And the analysis on water saving benefit of cotton under mulched drip irrigation was done. Results indicate that water requirements for the irrigated cotton are 543 mm in Tarim Irrigated Area. The water requirements of seedling stage is 252 mm, budding stage is 186 mm, bolling stage is 316 mm and wadding stage is 139 mm. the irrigation amount determines the spatial distribution of soil moisture and water consumption during cotton life cycle. However, water consumption at different growth stages was inconsistent with irrigation. Quantitatively, the water consumed by cotton decreases upon the increase of irrigation amount. From the perspective of water saving, the maximal water use efficiency can reach $3091 \text{ m}^3/\text{ha}$. But the highest cotton yield needs $3464 \text{ m}^3/\text{ha}$ irrigation water. In summary, compared to the conventional drip irrigation, a number of benefits in water saving and yield increase were observed when using plastic mulch. At the same amount of irrigation, the cotton yield with plastic mulch was 30.2% higher than conventional approaches, and the efficiency of water utilization increased by 30.2%. While at the same yield level, 29.3% water was saved by using plastic mulch, and the efficiency increased by 41.5%.

Key words Key words Cotton's water demand, Cotton's water consumption, Water-saving benefits, Drip irrigation with plastic film mulch

1 Introduction

The drip irrigation with plastic film mulch is the most efficient water-saving irrigation technique for Xinjiang oasis agriculture, and the water and salt transport law of cotton field under drip irrigation with plastic film mulch draws widespread concern of scholars. Domestic scholars have conducted in-depth studies on the soil and water movement and its influencing factors under drip irrigation as well as the factors that affect wetted material transport^[1-8]. There has been significant progress in the studies on soil salt transport, distribution and accumulation of cotton field under drip irrigation with plastic film mulch^[9-11]. Sun Lin *et al.*^[12] also predict the soil salinity trends of cotton field under long-term drip irrigation. Wang Youke *et al.*^[13] also discuss the water-saving and yield-increasing irrigation mode. The drip irrigation with plastic film mulch has changed the previous water movement law, and the crop's water demand and irrigation system under ordinary irrigation can not be entirely same as that under drip irrigation with plastic film mulch. However, currently, there is still a shortage of studies on cotton's water demand and water consumption, water-saving and yield-increasing benefit, and appropriate irrigation system under drip irrigation with plastic film mulch. Scholars have achieved some results on the study of cotton's water demand and water con-

sumption and irrigation system under drip irrigation with plastic film mulch in northern Xinjiang^[14-15]. The studies on the crop's water demand in southern Xinjiang are mainly based on ordinary irrigation, and the water demand calculation model for some crops has been established through long-term studies^[16-17]. However, few studies are about the cotton's water demand and irrigation system under drip irrigation with plastic film mulch. Liu Xinyong *et al.*^[18] study the cotton's water consumption and irrigation system under drip irrigation with plastic film mulch in southern Xinjiang, but it still can not meet the cotton cultivation and extension needs under drip irrigation with plastic film mulch in entire southern Xinjiang. Comprehensive understanding the cotton's water demand and water consumption under drip irrigation with plastic film mulch, and making a comparative analysis of water use efficiency and water-saving benefits under different irrigation patterns, is of great significance to developing water-saving agriculture, strengthening intensive management of water resources, improving water use efficiency, and predicting cotton yield. However, in southern Xinjiang with water scarcity, it still lacks the studies on cotton's water demand, irrigation system and cotton's water production function under drip irrigation with plastic film mulch, and especially the water use efficiency and water-saving benefits under different irrigation patterns. Therefore, through the field plot experiment with different amounts of irrigation, this paper uses the dynamic water monitoring data and water balance theory to study the cotton's water consumption at growth stage under drip irrigation with plastic film mulch in Tarim Irrigated Area, to determine the

Received: February 13, 2016 Accepted: April 13, 2016

Supported by 973 Project (2009CB421302); Innovation Project of Chinese Academy of Sciences (KZCX2-YW-127); Youth Science Foundation of China (41401025).

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water balance and conversion relationship between various elements in cotton field under drip irrigation with plastic film mulch, and establish the quantitative relationship between cotton yield and amount of irrigation under drip irrigation with plastic film mulch and ordinary flood irrigation. This paper makes an analysis of water-saving benefits under drip irrigation with plastic film mulch in order to provide a theoretical basis for the scientific irrigation and rational allocation of limited water resources in Tarim Irrigated Area.

2 Materials and methods

2.1 Overview of the study area The experiment was carried out in Aksu Agroecosystem National Field Research Station of Chinese Academy of Sciences ($40^{\circ}37'N$, $80^{\circ}45'E$) during 2005 – 2012. The study area has a warm temperate arid climate, with the annual average temperature of $11.2^{\circ}C$. Compared with the same latitude regions, the temperature is very high in summer but quite low in winter, and the spring and autumn temperature changes violently. The annual rainfall is 45.7 mm; the annual water surface evaporation is 2500 mm; the frost-free period is 207 d; the number of annual sunshine hours is 2940; the total annual solar radiation is 6000 MJ/m^2 . The soil is silt loam.

2.2 Experimental design The experiment uses the randomized plot design, and irrigation volume has six levels, namely $4265\text{ m}^3/\text{ha}$ (I), $3926\text{ m}^3/\text{ha}$ (II), $3600\text{ m}^3/\text{ha}$ (III), $3271\text{ m}^3/\text{ha}$ (IV), $2947\text{ m}^3/\text{ha}$ (V), $2618\text{ m}^3/\text{ha}$ (VI). Each treatment is repeated four times, and the plot area is 389.2 m^2 . The cotton variety for experiment is Zhongmian 49, and the spacing in the rows and spacing between rows use the wide and narrow row spacing configuration $[(10 + 65 + 10 + 60)\text{ cm}]$, namely 4 rows of cotton is planted under each film, with narrow row spacing of 10 cm, wide row spacing of 65 cm, film spacing of 60 cm and row spacing of 10 cm. It was planted on April 28, and 450 kg/ha of DAP was applied as basal fertilizer before planting. As to the irrigation during the whole growth period, it uses drip irrigation mode, and the drip irrigation belt is in the middle of wide rows. The drip irrigation is conducted every 7 days, and the irrigation lasts for 7 – 11 h. It was irrigated for the first time on June 24 (bud stage), and it was irrigated for a total of 10 times. During the irrigation for the third time to sixth time, 450 kg/ha of urea and 150 kg/ha of potassium dihydrogen phosphate are applied.

2.3 Research methods

2.3.1 Soil moisture observation. Under different moisture treatment, the neutron tube is laid in the wide cotton rows, narrow rows and between film, respectively, and the neutron moisture meter (CNC503DR) is used to measure the $0 - 20$, $20 - 40$, $40 - 60$, $60 - 80$ and $80 - 100\text{ cm}$ soil water content. It is measured once every 2 d, and it is tested around drip irrigation. In order to solve the inaccuracy of neutron instrument in measuring surface soil moisture, the drying method is used for neutron instrument calibration.

2.3.2 Evapotranspiration of reference crop (ET_0). Using the

Penman-Monteith equation recommended by FAO (Smith, 1991), we calculate the evapotranspiration of reference crop (ET_0)^[19]:

$$ET_0 = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T + 273}u_2(e_a - e_d)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where ET_0 is the evapotranspiration of reference crop (mm); R_n is the net radiation of crop surface [MJ/($\text{m}^2 \cdot \text{d}$)]; G is the soil heat flux [MJ/($\text{m}^2 \cdot \text{d}$)]; T is the daily average temperature ($^{\circ}\text{C}$); u_2 is 2 m high average daily wind speed (m/s); $e_a - e_d$ is the saturated water vapor pressure (kPa); Δ is the slope of saturated water pressure – temperature curve (kPa/ $^{\circ}\text{C}$); γ is the psychrometric constant (kPa/ $^{\circ}\text{C}$).

According to the annual meteorological data of Aksu Research Station, we calculate the evapotranspiration of reference crop (ET_0) by the above equation.

2.3.3 Cotton's water demand (ET_c) and crop coefficient (K_c) under drip irrigation with plastic film mulch. The mathematical model between cotton's water demand and its influencing factors is as follows:

$$ET_c = K_c \times ET_0 \quad (2)$$

where ET_c is crop's water demand (mm); ET_0 is the evapotranspiration of reference crop (mm); K_c is the crop coefficient.

First, we calculate ET_0 , and then measure ET_c in the full wet soil conditions. The ratio of the two is the cotton coefficient K_c under drip irrigation with plastic film mulch.

2.3.4 Cotton's water consumption under drip irrigation with plastic film mulch. According to the field water balance principle^[20], the simplified formula of cotton field water balance under drip irrigation with plastic film mulch is as follows:

$$ET = I - (W_2 - W_1) - BW \quad (3)$$

where ET is cotton's water consumption (mm); W_1 is the 100 cm soil water storage at the beginning of period (mm); W_2 is the 100 cm soil water storage at the end of period (mm); I is the irrigation amount (mm); BW is the water exchange capacity under root layer (100 cm) (mm).

By equation (3), we calculate cotton's water consumption; by Darcy's law, we calculate the root layer fluxes.

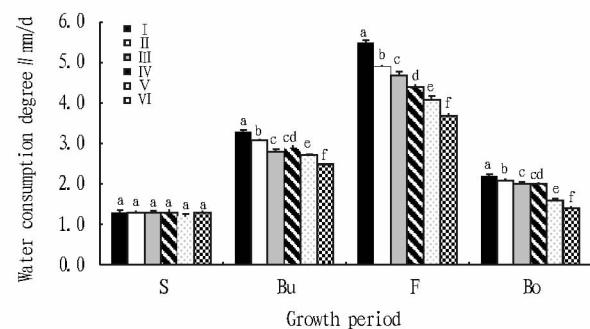
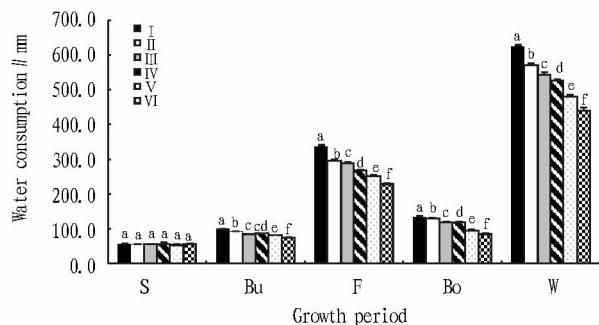
2.3.5 Data processing. One-way ANOVA is used to process data. If ANOVA results are significant, then the least significant difference (LSD) method is used for pairwise multiple comparison. All statistical analyses are completed by Excel and SPSS 13.0.

3 Results and analysis

3.1 Cotton's water consumption and water consumption rule under drip irrigation with plastic film mulch Fig. 1 shows that drip irrigation has a significant impact on cotton's water consumption, and with decreasing drip irrigation, cotton's total water consumption is reduced. Under each treatment, cotton's water consumption is highest at blossoming and boll-forming stage, followed by the consumption at bud stage, and the consumption is low at seedling stage and boll-opening stage. There is no significant difference in cotton's daily water consumption degree at seed-

ling stage between different treatments, with value of 1.2–1.3 mm/d; after bud stage, the daily water consumption degree increases with increasing drip irrigation; at bud stage, the cotton's daily water consumption degree under various treatments is 2.5–3.3 mm/d; after blossoming and boll-forming stage, the daily water consumption degree peaks, with value of 3.7–5.5 mm/d; at boll-opening stage, it decreases to about 1.4–2.2 mm/d. Obviously, the blossoming and boll-forming stage of cotton under drip irrigation with plastic film mulch is the stage with the highest water consumption degree in its growth period, and the water consumption accounts for 50% of total water consumption in whole growth period; the water consumption degree is lower at boll-opening

stage, seedling stage and boll-opening stage. As can be seen from Fig. 2 there is a significant difference in the share of the water consumption in total water consumption (modulus coefficient) between different treatments; the share is smallest at seedling stage, reaching 8.9%–12.5%; the share is largest at blossoming and boll-forming stage, reaching 51.6%–53.8%; it is 15.4%–16.8% at bud stage and 19.1%–22.5% at boll-opening stage, but there is no significant difference between treatments. It indicates that the drip irrigation only affects the cotton's water consumption, and does not affect the share of water consumption at each stage.



Note: Different lowercase letters indicate significant differences between treatments ($P < 0.05$), the same as below. S: Seedling stage; Bu: Budding stage; F: Flowering and bolling stage; Bo: Boll opening stage; W: Whole growth period. The same below.

Fig. 1 Cotton's water consumption at different growth stages under different water treatments

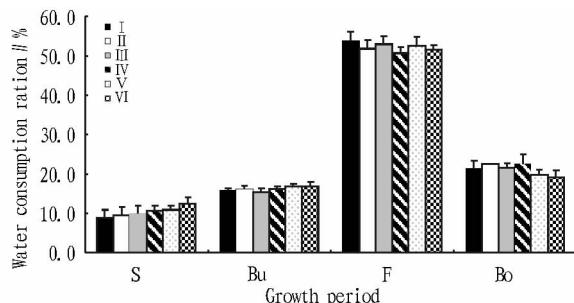


Fig. 2 Share of cotton's water consumption in total water consumption between different treatments at various growth stages

Unit: %

Table 1 Cotton's water demand and rules under drip irrigation with plastic film mulch

Growth period	Number of days	Reference crop evapotranspiration mm	Crop coefficient	Water demand mm	Water demand intensity mm/d	Modulus coefficient %
month-day	d	mm				
Seedling stage (04–25–06–08)	43	251.9 ± 7.0a	0.22 ± 0.003a	54.4 ± 1.4a	1.3 ± 0.03a	10.0 ± 2.0a
Bud stage (06–08–07–08)	30	186.0 ± 6.0b	0.45 ± 0.010b	83.5 ± 1.7b	2.8 ± 0.06b	15.4 ± 1.0a
Blossoming and boll-forming stage (07–08–09–07)	61	315.7 ± 4.5c	0.91 ± 0.010c	288.0 ± 4.3c	4.7 ± 0.07c	53.0 ± 2.0a
Boll-opening stage (09–07–11–07)	60	139.3 ± 6.1d	0.84 ± 0.03d	117.3 ± 3.1d	1.9 ± 0.05d	21.6 ± 1.2a
Whole growth period	194	892.9	0.61	543.2	2.7	100.0

2.8 mm/d; the water demand is 117.3 mm at boll-opening stage, 21.6% of total water demand in the growth period, and the water demand intensity is 1.9 mm/d.

3.3 Cotton's water production function under drip irrigation with plastic film mulch The relationship between seed cot-

ton yield under drip irrigation with plastic film mulch (Y) and drip irrigation amount in the growth period (I) is shown in Fig. 3. Through the regression analysis, it is found that there is a second-degree parabolic relationship between the two:

$$Y = -0.0026I^2 + 18.015I - 24845 \quad (R^2 = 0.9592, n = 6) \quad (1)$$

To analyze the effect of irrigation, we introduce two basic concepts, namely average irrigation yield (AI) and marginal irrigation yield (MI). We define AI as the average yield per unit of irrigation amount^[21] (namely irrigation water use efficiency), and define MI as the additional yield by increasing certain units of irrigation amount. It is the first-order derivative of $Y - I$ relationship, and the unit of AI and MI is $\text{kg}/(\text{ha} \cdot \text{m}^3)$.

$$MI = dY/dI = 18.015 - 0.0052I \quad (2)$$

$$AI = Y/I = 18.015 - 0.0026I - (24845/I) \quad (3)$$

Fig. 3 shows that three curves have two important turning points dividing $Y - I$ curve into three sections. (i) The first point is the intersection point (C) of $MI - I$ curve and $AI - I$ curve, the highest point of average yield curve, and the marginal yield at this point is equal to the average yield; the maximum irrigation water use efficiency is $1.941 \text{ kg}/(\text{ha} \cdot \text{m}^3)$, and the corresponding drip irrigation is $3091 \text{ m}^3/\text{ha}$. (ii) The second point is the highest point (D) of $Y - I$ curve, and the marginal yield MI at this point is zero. The maximum yield is $6360 \text{ kg}/\text{ha}$, the drip irrigation amount is $3464 \text{ m}^3/\text{ha}$, and the irrigation water use efficiency is $1.836 \text{ kg}/(\text{ha} \cdot \text{m}^3)$. The first section of curve is from original point to point D , the marginal yield is greater than the average yield, and the growth rate of yield is higher than that of irrigation amount. It is the cotton water scarcity area, and the increase of irrigation amount in this section will significantly increase yield, so it is necessary to increase water input as long as there is enough water. The second section is from C to D , and the marginal yield is greater than zero, but less than the average yield. The growth rate of yield is lower than that of irrigation amount, and it is the water-deficient and water-regulatory area. The adjusted drip irrigation amount is $3091 - 3464 \text{ m}^3/\text{ha}$, and when drip irrigation amount reaches $3464 \text{ m}^3/\text{ha}$, the yield is highest. The third section is after D , and the marginal yield is less than zero. The yield decreases with the increasing irrigation amount, and it is the wasteful irrigation area.

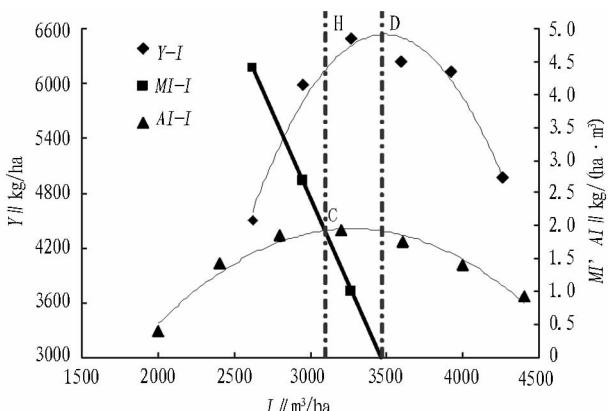


Fig. 3 The relationship between irrigation amount and cotton yield, average yield or marginal yield under drip irrigation with plastic film mulch

3.4 Water-saving benefits of cotton field under drip irrigation with plastic film mulch Under drip irrigation with plastic film mulch and ordinary flood irrigation, the relationship between cotton yield and irrigation amount is shown in Fig. 4, and through regression analysis, it is found that there is a second-degree parabolic relationship. The relationship between cotton yield under drip irrigation with plastic film mulch and drip irrigation amount is shown in equation (1). The relationship between cotton yield under ordinary flood irrigation and irrigation amount is as follows:

$$Y = -0.000973I^2 + 7.5986I - 9761.7 \quad (R^2 = 0.9672, n = 6) \quad (4)$$

As can be seen from Fig. 4, when the irrigation amount is less than $3464 \text{ m}^3/\text{ha}$, the cotton yield under both irrigation modes increases with the increasing irrigation amount, the cotton yield under drip irrigation with plastic film mulch is greater than under ordinary flood irrigation, indicating that the sensitivity of cotton to irrigation water under drip irrigation with plastic film mulch is greater than under ordinary flood irrigation. When the irrigation amount is increased to $3464 \text{ m}^3/\text{ha}$ (G), the cotton yield ($6360 \text{ kg}/\text{ha}$) peaks under drip irrigation with plastic film mulch, and the irrigation water use efficiency is $1.836 \text{ kg}/(\text{ha} \cdot \text{m}^3)$. At this point, the cotton yield under ordinary flood irrigation is $4885 \text{ kg}/\text{ha}$, and irrigation water use efficiency is $1.410 \text{ kg}/(\text{ha} \cdot \text{m}^3)$. The yield increases by 30.2% under drip irrigation with plastic film mulch, and irrigation water use efficiency increases by 30.2% . When the irrigation amount is $3464 - 3905 \text{ m}^3/\text{ha}$, the cotton yield under drip irrigation with plastic film mulch will decrease with increasing irrigation amount, while the cotton yield under the ordinary flood irrigation will continue to increase with the increasing irrigation amount. When the irrigation amount increases to $3905 \text{ m}^3/\text{ha}$ (H), the cotton yield under the ordinary flood irrigation reaches the maximum of $5074 \text{ kg}/\text{ha}$, and the irrigation water use efficiency is $1.299 \text{ kg}/(\text{ha} \cdot \text{m}^3)$. When the cotton yield under drip irrigation with plastic film mulch is equal to the maximum cotton yield under the ordinary flood irrigation, the drip irrigation amount is $2761 \text{ m}^3/\text{ha}$, and the irrigation water use efficiency is $1.838 \text{ kg}/(\text{ha} \cdot \text{m}^3)$, saving 29.3% of water compared with the ordinary flood irrigation. When the irrigation amount is greater than $3905 \text{ m}^3/\text{ha}$, the cotton yield under two irrigation modes will decrease with the increasing irrigation amount. When the cotton yield under two irrigation modes reaches maximum, drip irrigation with plastic film mulch cotton will save 11.3% of water, increase 25.3% of production and improve 41.3% of irrigation water use efficiency compared with the ordinary flood irrigation.

4 Conclusions and discussions

The water demand of cotton under drip irrigation with plastic film mulch in the whole growth period is 543 mm in Tarim Irrigated Area; the water demand is lowest at seedling stage, accounting for 10% of total water demand in the growth period; the water demand is highest at blossoming and boll-forming stage, accounting for 53% ; the water demand at bud stage and boll-opening stage

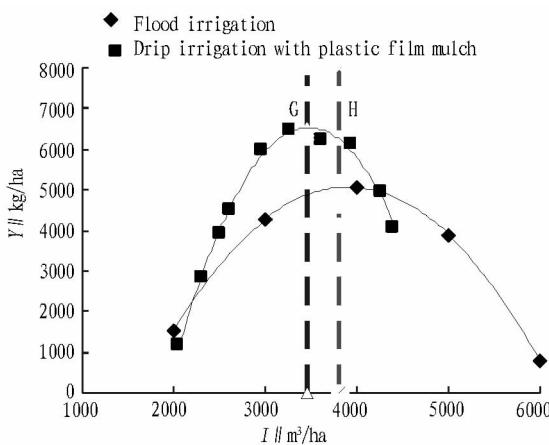


Fig. 4 Relationship between drip irrigation amount and cotton yield under different irrigation modes

accounts for 15.4% and 21.6%, respectively. Under different drip irrigation amount, there is a difference between cotton's actual water consumption and water demand, showing different levels of profit and loss. When the drip irrigation amount is $3600 m^3/ha$, the water supply and demand are balanced. The drip irrigation amount directly affects the cotton yield and irrigation water use efficiency, and there is a second-degree parabolic relationship, following law of diminishing returns. However, the highest point of yield is not consistent with that of irrigation water use efficiency, while the drip irrigation amount when the irrigation water use efficiency is highest is lower than the drip irrigation amount when the yield is highest, so there is contradiction between saving water and increasing production. From the perspective of saving water, when the drip irrigation amount is $3091 m^3/ha$, the irrigation water use efficiency can be highest, but the cotton yield at this point is 5.7% lower than the highest yield. To obtain maximum yield, the drip irrigation amount should be $3464 m^3/ha$. When the drip irrigation amount is less than $3091 m^3/ha$, it is the cotton water scarcity area under drip irrigation with plastic film mulch, and it is necessary to increase irrigation if there is enough water; when the drip irrigation amount is $3091 - 3464 m^3/ha$, it is the water-deficient and water-regulatory area; when the drip irrigation amount is more than $3464 m^3/ha$, the yield will decrease with the increasing drip irrigation amount, and it is the wasteful irrigation area. Under the same management mode, the highest cotton yield under drip irrigation with plastic film mulch is higher than under the ordinary flood irrigation, and when both modes achieve the highest yield, the drip irrigation with plastic film mulch cotton will save 11.3% of water, increase 25.3% of production and improve 41.3% of irrigation water use efficiency compared with the ordinary flood irrigation. Under the same amount of irrigation, the yield increases by 30.2% and irrigation water use efficiency increases by 30.2% under drip irrigation with plastic film mulch, when compared with the ordinary flood irrigation. Under the same yield, drip irrigation with plastic film mulch will save 29.3% of water and increase 41.5% of irrigation water use efficiency compared

with the ordinary flood irrigation, indicating that at the current water use conditions and current cotton yield level under the ordinary flood irrigation, using the drip irrigation with plastic film mulch to develop water-saving agriculture has huge yield potential, and can greatly improve the irrigation water use efficiency. From the perspective of sustainable development, it is necessary to explore the environmental effects and soil salinity trends under drip irrigation with plastic film mulch, establish the technical suitability evaluation indicators for drip irrigation with plastic film mulch, and build the ecological security of water-saving agriculture and sustainability assessment mechanism in the arid area of oasis, which is the fundamental requirement of sustainable development of water-saving agriculture in Xinjiang and the northwestern arid areas.

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and technology enterprises.

4.5 Establishing and improving enterprise's culture of innovation and creative spirit

The agricultural science and technology enterprises should pay attention to innovation culture and creative spirit. Innovation culture refers to the cultural practice results precipitated in the innovation process, including the transition or upgrade in ideas, understanding methods, values, behavior and system mode. Enterprises provide many opportunities to learn innovation culture to stimulate the innovation spirit and beliefs of employees and form a good atmosphere of innovation culture within the enterprise. This will not only help to improve staff quality, create a favorable cultural environment for enterprises to carry out technological innovation, and greatly enhance the technological innovation capacity.

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