Sprinkler irrigation system for tea frost protection and the application effect

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Abstract: A sprinkler irrigation system was designed and applied for a tea field to achieve frost protection through latent heat release when water turning into ice. Frost protection effects during night were tested at different irrigation application rates by monitoring air temperature around tea canopy (T_c). Temperature sensors were arranged at different distances from the sprinkler. The preliminary results showed that, when the sprinkler system worked continuously at the application rate of 2-4 mm/h before sunrise, tea canopy was covered with ice and T_c remained around 0°C, preventing tea plants from frost damage. But no more temperature rise was obviously observed at the application rates above 4 mm/h, which means less cost effectiveness. The system was stopped after sunrise when background air temperature rose back to 0°C and T_c increased by 2.2°C in one hour, while T_c of non-irrigated area increased by 4.8°C, which might cause thawing injuries to tea plants. The leaf surface temperature was lower than T_c, and the difference between the leaf surface temperature and T_c decreased with the increase of application rate. Therefore, the sprinkler irrigation system could achieve tea frost protection, and the recommended application rate was 2-4 mm/h for better protection effect. The system should keep running throughout frost night till half an hour after sunrise. The start and stop of the sprinkler irrigation system should be controlled based on T_c.

Keywords: sprinkler irrigation, frost protection, *Camellia Sinensis* L, application rate, temperature rise, frost damage
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1 Introduction

Spring tea (*Camellia Sinensis* L.) in China has been suffering late frost damage for years since 2005. The production and quality of tea are affected seriously with great economic losses, restricting the sustainable development of tea industry[1]. The major frost protection methods in tea fields are flooding irrigation, covering, smoking, airflow disturbance of thermal inversion layer and so on. Flooding irrigation, covering and smoking usually have poor frost protection effects and are difficult to achieve automation. Wind machines or helicopters have a large investment and low utilization[2,3], while vertical blowing fans might require larger power and could be applied under certain conditions[4]. Therefore, exploring a method of low cost, no pollution and with good frost protection effect is quite significant in practice for tea production, which could realize the automation of frost protection equipment and improve its cost-effectiveness.

When water temperature falls from 20°C to 0°C, only 83.7 kJ/kg of sensible heat will be lost. However, when water freezes at 0°C, the phase change will convert 334.5 kJ/kg of latent heat to sensible heat[5]. Sprinkler

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irrigation can keep the temperature of tea leaves above critical temperature through the latent heat released from freezing water[6]. After the sprinkler irrigation is stopped, the ice attached to leaves begins to melt with sensible heat absorbed, thus the thawing damage due to the quick temperature recovery of tea leaves could be prevented.

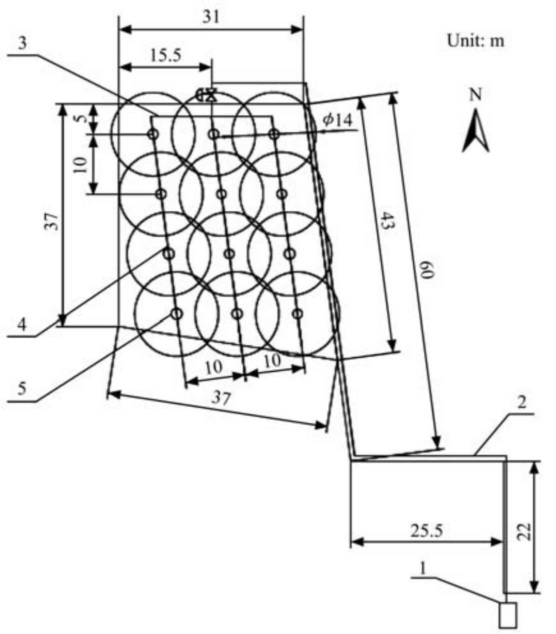
At present, sprinkler irrigation has been applied for frost protection in orchards or tea fields in some countries and have achieved good frost protection effects[7-11]. Based on the principle of heat and mass transfer, Barfield et al.[12] predicted the application rate of the sprinkler for night-time radiation frost protection on citrus. Anconelli et al.[13] investigated the efficiency of different sprinkler types and water volumes in enhancing air temperature in the canopy layer and optimized the amount and the cycling of the water applied. Issa[14] established a numerical model which could simulate frost protection process of a single citrus fruit. The effect of environmental conditions such as air temperature, air velocity, surface radiation and water film evaporation on the development of the ice layer encasing was considered in the simulation. Parsons et al.[15] used under-tree micro-sprinklers to prevent frost on citrus, with the temperature of leaves and trunks rising obviously compared to the non-irrigated area. In China, Zhang and Zeng[16] used the sprinklers for frost protection of forestry nursery and formulated the corresponding irrigation scheme, solving the frost problem of forestry nursery effectively with air temperature increased by 2.0°C -2.5°C. Yu and Yang[17] conducted research on frost protection using sprinkler system in vineyard. The test showed that the effect of air temperature rise in vineyard was significant, protecting grapes from frost damage with an increase of air temperature by 3.79°C-4.81°C. The method of washing frost with water was used in China to protect tea plant from frost damage. However, owing to lack of related research on frost protection using sprinkler system for tea fields, it is difficult to take control measures and determine an application rate without understanding the influence of spraying water on microclimate in tea fields, resulting in poor protection effects, over-irrigation and even waterlog in tea fields. In this study, a sprinkler irrigation system was designed and applied for tea frost protection, and tea canopy temperature changes were monitored during its operation. Then the influence of sprinkler irrigation on microclimate and frost protection effect at different application rates were studied through the analysis of frost protection principle using the system.

2 Design of sprinkler system for frost protection

2.1 System layout

The sprinkler system for frost protection was conducted on Maichun Tea Farm in Danyang, China. The general layout of sprinkler system is shown in Figure 1. The sprinkler system covers 2.2 acres of tea field with a 5° slope.

The sprinkler system was set up in the field with main and distribution pipes buried 30 cm deep in the soil. The irrigated water was lifted from a pond with a pump. In order to reduce the pressure difference between sprinklers and improve the uniformity of spraying water, lateral pipes were laid along the slope.



1. Pump station 2. Main pipe 3. Distribution pipe 4. Lateral pipe 5. Sprinkler

Figure 1 General layout of the sprinkler system

2.2 Selection and arrangement of sprinklers

2.2.1 Selection of sprinklers

Plastic impact-driven sprinklers were selected for its simple installation, low price and high quality[18], as shown in Figure 2. Before all the spraying water on tea leaf surface freezes, there must be new spraying water attached to leaves[19]. Thus, the rotation cycle of the sprinkler should be as short as possible. Technical parameters of the sprinklers are listed in Table 1.

Figure 2 Frost protection sprinkler

Table 1 Technical parameters of the sprinkler

Operating pressure/MPa	Nozzle diameter/ mm	Flow rate/ $m^3 \cdot h^{-1}$	Pattern radius/m	Rotation cycle/ s
0.3	3	0.4	7	18

2.2.2 Arrangement of sprinklers

Most of the frosts are radiation frosts[20] that occur during less or no wind night[5]. Therefore, the sprinkler system ran within the wind speed of 0.3-1.6 m/s, and the sprinklers were arranged in square. The sprinkler spacing was determined as 9 m due to the 1.5 m-row spacing in the field. The application rate of the sprinkler system was 3.9 mm/h through calculation.

The allowable application rate of the tea fields is 8 mm/h. The overlapped application rate calculated is less than the allowable application rate so as to meet the design requirements[21].

2.3 Selection of pipes

In general, material of fixed pipes buried underground is plastic. Plastic pipe has the advantage of light weight, smooth wall, corrosion resistant and small head loss. Furthermore, it is easy to handle, construct and able to adapt to a certain uneven subsidence[18]. Hence UPVC (Unplasticized polyvinyl chloride) material was selected for the sprinkler system. Through the calculation of head loss, the sizes of lateral pipe, distribution pipe and main pipe are 20 mm, 25 mm and 40 mm respectively with the reference of design handbook.

2.4 Selection of pump

The flow rate of the system was 4.9 m^3/h and the lift needed in the sprinkler system was 44.99 m through hydraulic calculation.

Based on flow rate and lift, a pump of 40ZX6.3-50 was selected and its specification is shown in Table 2.

Table 2 Pump specification

Caliber/ mm	Flow rate/ $m^3 \cdot h^{-1}$	Lift/ m	Power/ kW	Rotation speed/ $r \cdot min^{-1}$	Self-priming lift/ m
40	6.3	50	4	2900	6.5

3 Experiment of frost protection with sprinklers

3.1 Materials

The experiment was conducted on Maichun Tea Farm (32°01′33″N, 119°40′22″E, altitude of 18 m, hilly terrain) from January to March, 2014. The tea variety was seven-year-old Anji white tea. The sprinkler system for the experiment is shown in Figure 1. The measuring instruments are: ZDR-3WIS automatic temperature recorder (Hangzhou Zeda Company) with measurement accuracy of ±0.1°C and measurement range of –50°C-100°C; NK4000 Portable Anemometer (Spectrum Corporation) with measurement parameters of air temperature, humidity, radiation, wind speed, wind direction and rainfall; Ti55 IR FlexCam Thermal Imager (Fluke Corporation) with measurement accuracy of ±0.2°C and measurement range of −20°C-600°C; 830-T4 Infrared Thermometer (Testo Industry Corporation) with measurement accuracy of ±1.5°C in the measurement range –20°C-0°C; rain gauges.

3.2 Methods

3.2.1 Sprinkler irrigation at constant application rate

The experiment of frost protection effect at a constant application rate of 3.9 mm/h was conducted from the night of February 20th to the morning of February 21st, 2014. Air temperature around tea canopy (T_c) and water temperature were recorded every 15 min with ZDR-3W1S temperature recorders in the irrigated area, non-irrigated area and 0.5 m deep below pond water level, respectively. The ice surface temperature was measured with Ti55 IR FlexCam Thermal Imager. A psychrometer was hanged in the tea field at a height of 1.5 m above the ground to measure wet bulb temperature

T_b. The sprinkler irrigation system was started when wet bulb temperature dropped to 0°C and stopped when it reached 0°C after sunrise.

3.2.2 Sprinkler irrigation at different application rates

To compare frost protection effects at different application rates, three sprinklers without mutual interference were used for frost protection from the night of March 20th to the morning of March 21st, 2014. Rain gauges were arranged along the distances of 0 m, 2 m, 4 m, 6 m, 7 m, 8 m, 9 m, and 10 m from the sprinkler to measure the sprinkler application rate at every distance, as shown in Figure 3. The variation of T_c and the dynamic change of water temperature were monitored every 10 min in the irrigated area, non-irrigated area and 0.5 m deep below pond water level. The temperature of ice on leaf surface at every distance was measured with 830-T4 Infrared Thermometer. The psychrometer was hanged above the tea field at a height of 1.5 m above the ground to measure wet bulb temperature T_b. The sprinkler irrigation system was started when T_b dropped to 0°C and stopped when it reached 0°C after sunrise.

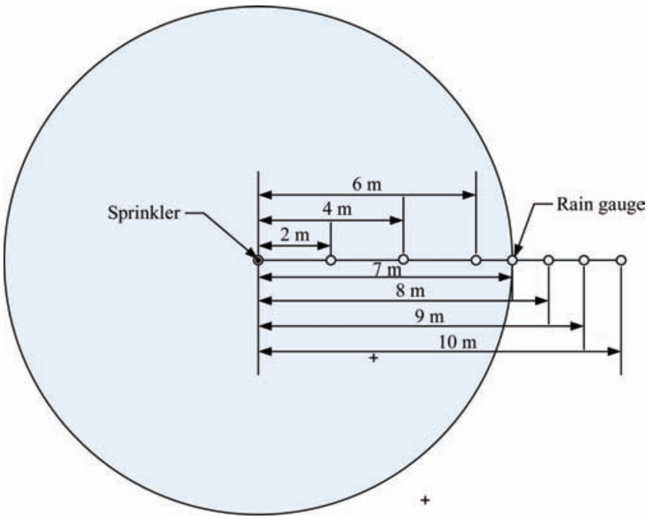


Figure 3 Layout of rain gauges

3.3 Results and analysis

3.3.1 Frost protection effect at constant application rate

During frost nights, water should be sprayed onto tea leaf surface continuously[22]. In the experiment, the sprinkler system was started at 23:45 on February 20th and stopped at 08:00 on February 21st. The temperature at 0.5 m deep below pond water level remained 5-6°C. The sky was clear with no wind at night and the sun rose at 06:37. Frost was visible on the surfaces of tea leaves in non-irrigated area. Results of the dynamic change of T_c monitored in irrigated and non-irrigated areas are shown in Figure 4. The sprinkler system was started when T_b was 0°C, but T_c was –3.4°C with visible frost. This indicated that the start and stop of the sprinkler irrigation system should be implemented mainly based on tea canopy temperature. After the sprinkler irrigation system was started, T_c rose obviously, and then kept around 0°C till the system was stopped. T_c of non-irrigated area was below –1.5°C with its minimum of –4.7°C.

After frost occurs, leaf cells may recover if ice thaws slowly, whereas quick thaw could lead to a rapid temperature rise and then stress injuries will occur to cells and cause damage[23]. In the period of 07:00-09:00, T_c of non-irrigated area rose quickly from –3.8°C to 4.5°C, causing stress injuries to tea leaves easily. After the system was stopped, T_c of irrigated area increased by 2.2°C in one hour, while T_c of non-irrigated area increased by 4.8°C. The sprinkler irrigation slowed down the temperature rise by 54% which could effectively avoid thawing damage.

Surface temperature of tea leaves was monitored with Ti55 IR FlexCam Thermal Imager in irrigated and non-irrigated area at 07:00 on February 21st. The effect of sprinkler irrigation on T_c is shown in Figure 5. The average surface temperature of tea leaves in non-irrigated area was –2.7°C with the minimum of –3.6°C. The average surface temperature of the leaves in irrigated area was 0.3°C with the minimum of –0.3°C. Average surface temperature of the leaves in irrigated area was 3°C higher than that in non-irrigated area.

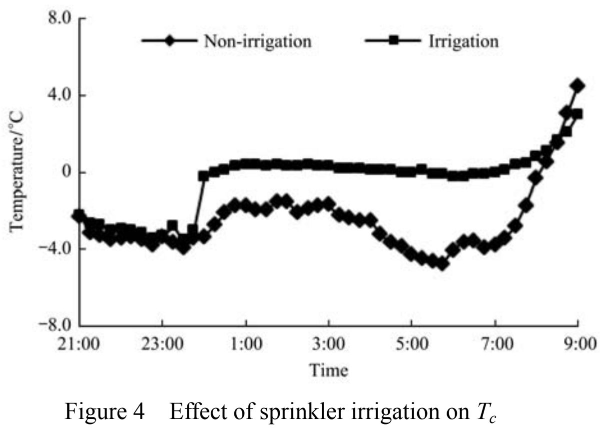


Figure 4 Effect of sprinkler irrigation on T_c

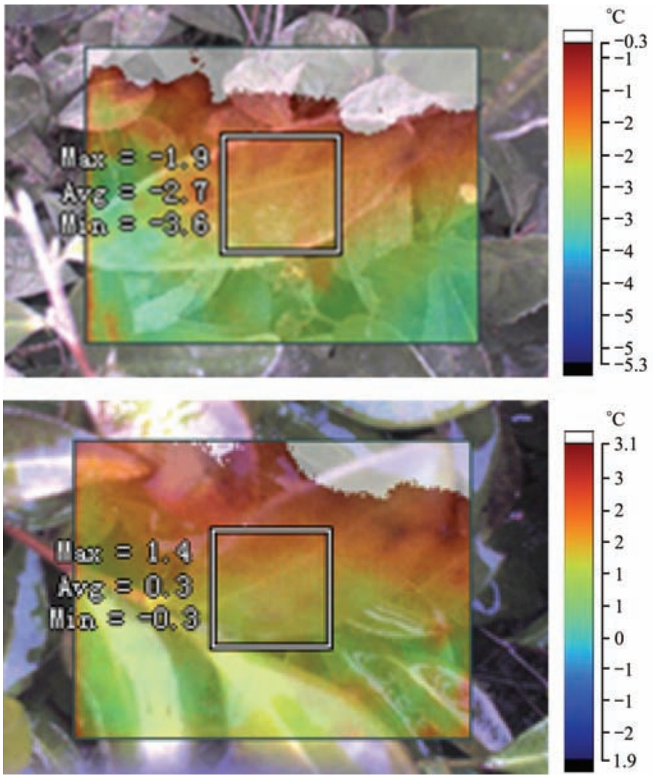


Figure 5 Leaf surface temperature in irrigated (left) and non-irrigated (right) area

3.3.2 Frost protection effect at different application rates

The spraying water is nonuniform when a single sprinkler works[24]. The application rate at different distance from the sprinkler is shown in Table 3. It showed that the application rate decreased with the distance from the sprinkler and no spraying water was collected at the distance of 10 m. The frost protection sprinklers were started at 02:30 and stopped at 06:46 on March 21st. The temperature recorded at 0.5 m deep below the pond water level was 11°C-12°C. The sky was clear with no wind at night and the sun rose at 06:03 on next morning. In non-irrigated area, frost was obviously observed on the tea leaf surface. Results of the dynamic change of T_c at different application rates and in non-irrigated area are shown in Figure 6. In early spring, frost resistance of tea trees abated and the critical temperature was –3°C during bud stage and –2°C during 2-leaf stage[25,26]. Freeze injury is closely related to cellular dehydration induced by freezing temperature[27]. In the period of 02:30-06:00, under certain meteorological conditions, average T_c of non-irrigated area was –2°C with –2.9°C as the minimum temperature, which could cause frost damage to tea buds. In areas where the application rate was between 0-2 mm/h, the average T_c was –1.6°C with –2.3°C as the minimum temperature. Although T_c at the application rate of 0-2 mm/h was higher than that of non-irrigated area, frost damage occurred because of the low application rate, which could not offer enough heat to increase tea canopy temperature above critical temperature. The application rate of 2-4 mm/h could keep tea canopy temperature around 0°C with –0.5°C as the minimum, which prevented frost damage. The average tea canopy temperature in the area at the application rate of 4-8 mm/h was 0.4°C with the minimum of 0°C.

Although frost protection effect achieved in the irrigated area within 4-8 mm/h application rate was better than that within 2-4 mm/h application rate, the difference of temperature rise was not significant. Therefore, application rates above 4 mm/h under such weather conditions should not be recommended since it would results in waste of water and waterlog in tea fields. The above argument was confirmed by the fact that when 1.0 kg water freezes at 0°C, latent heat released is about four times that of the sensible heat released from 1.0 kg water when its temperature falls from 20°C to 0°C[5] . If the application rate is still too large after T_c rising to 0°C, most heat contained in spraying water will not contribute more to frost protection, since unfrozen water weakens the effect of temperature rise when the application rate increases.

Table 3 Application rate at different distances from the sprinkler

Distance/m	0	2	4	6	7	8	9	10
Application rate/mm·h^{-1}	8	4.5	3.7	2.8	2.6	2.4	1.1	0

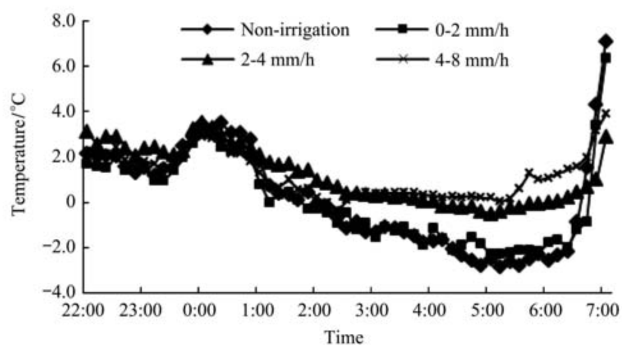


Figure 6 Effect on T_c at different application rates

The temperature of surface ice at different application rates and leaf temperature in non-irrigated area were monitored with 830-T4 infrared thermometer at 05:00 on March 21st, and the results are shown in Figure 7. The leaf surface temperature was lower than T_c at all distances and the difference between the leaf surface temperature and T_c decreased with the increase of the application rate. The largest temperature difference between irrigated area with 0-2 mm/h application rate and non-irrigated area was 0.6°C. Leaf surface temperature was higher than critical temperature within the application rates of 2-4 mm/h and 4-8 mm/h during 1-2 leaf stage.

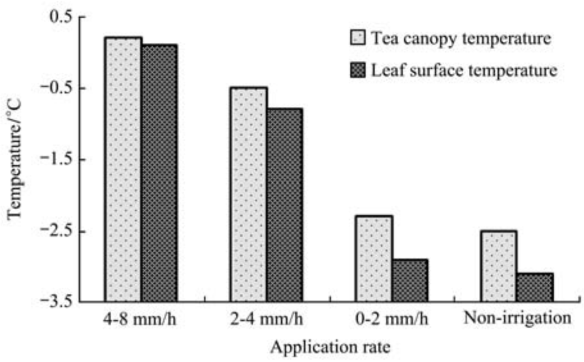


Figure 7 Effect on leaf surface temperature at different application rates

4 Conclusions and prospect

The results show that the sprinkler irrigation system could keep tea canopy temperature around 0°C during frost nights and delay tea canopy temperature recovery after sunrise, therefore prevent the occurrence of frost in tea fields. The application rate should be determined with respect to the prevailing weather conditions during frost nights since over-irrigation would result in not only waste of water but also some problems associated with waterlog in tea fields. In early spring with the minimum temperature of –1°C, the application rate of 2-4 mm/h was enough to achieve the necessary frost protection effect. The system should keep working through the whole night till half an hour after sunrise. The start and stop of the sprinkler irrigation system should be implemented based on temperature around tea canopy.

The preliminary experimental study was conducted on the sprinkler frost protection effect at different application rates. The application rate needed in frost protection varied with the weather condition such as air temperature, humidity, and wind speed. Sprinkler irrigation has the expanding application potential by studying the effect of different application rates on frost protection for better control decisions. The required application rate under different weather conditions should be further studied based on this study and the principle of heat and mass transfer. Then a control strategy should be put forward and an application rate controller will be developed to achieve better frost protection effect with water-saving sprinkler irrigation.

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