Translated Report

Water Requirements of Drip-Irrigated Cabbage at Coastal Arid Lands of the California Peninsula, Mexico

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Abstract The irrigation water requirements of cabbage for maximum yield with minimum water use were investigated based on meteorological conditions and soil moisture dynamics at coastal areas in the California peninsula, Mexico. Six water levels corresponding to 0.9, 1.3, 1.45, 1.7, 1.8, and 1.9 \( ET_p \) (\( ET_p \)=potential evapotranspiration calculated from the Penman method) were applied as irrigation water under drip conditions. The yield of cabbage at the water levels of 0.9 and 1.3 \( ET_p \) was low in comparison with that at 1.45 \( ET_p \). No significant yield differences were obtained between the 1.45 and 1.9 \( ET_p \) levels. Under these conditions, 1.45 \( ET_p \) is shown to be the optimal water requirement of cabbage for saving water and obtaining high yield. It was also shown that the soil moisture depletion in the root zone of cabbage was about 1.5 times the potential evapotranspiration.

I. Introduction

It is very important for sustainable agriculture in arid lands, where rainfed farming is not practical, to evaluate adequate irrigation water requirements for the purpose of saving water. In this study, the water requirements of drip-irrigated cabbage in coastal arid lands (N. lat. 28°, W. long. 114°) of the California peninsula, Mexico, where annual rainfall and pan evaporation are 80 mm/y and 1400 mm/y respectively, were investigated based on meteorological data and soil moisture dynamics in the cabbage root zone. For this purpose, the potential evapotranspiration(\( ET_p \)) was calculated from the modified Penman method\(^1\) using meteorological data measured at the study site. Six kinds of crop coefficients (\( k=0.9, 1.3, 1.45, 1.7, 1.8, \) and 1.9) were employed for each experimental treatment. The amount of water applied in each treatment was calculated by \( k, ET_p \). The yield of cabbage for different amounts of applied water was investigated. Soil moisture in the cabbage field was also measured to investigate the relationship between potential evapotranspiration and soil moisture depletion due to water uptake by cabbage roots.

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II. Study Area

The study field is located at Guerrero Negro of the Viscaino desert in Baja California, Mexico\(^2\). The size of the field is 2 ha. Figure 1 shows the monthly changes in rainfall \((R)\), and class A pan evaporation \((E_{\text{pan}})\) from April 1992 to February 1994. The potential evapotranspiration \((ET_p)\) was calculated by the modified Penman method\(^1\), based on the measured data for air temperature, relative humidity, wind speed, and solar radiation from the meteorological observation station installed at the study site. An adjustment factor to compensate for the effect of day and night weather conditions ranged from 0.8 to 1.15.

The rainfall at the study site occurs mainly during the winter season, although two-day successive rainfalls of 8 mm/d and 7 mm/d were observed in August 1992. Annual rainfall is only 80 mm/y. Pan evaporation was at a maximum in July 1992 and July 1993. The daily mean value of pan evaporation is 5.7 mm/d, and annual pan evaporation was 1400 mm/y in 1993. Monthly changes in the potential evapotranspiration \(ET_p\) show a trend similar to changes in pan evaporation \(E_{\text{pan}}\).

Figure 2 shows monthly changes in air temperature, relative humidity, wind speed, and solar radiation in 1993. The Max., Mean, and Min. in Figure 2 indicate the mean values of the maximum, the mean, and the minimum values in hourly data for one day. The Tokyo radiation data refer to the values listed in the chronological scientific tables\(^3\). Since the study site is in a coastal area, humidity increases during the night and decreases during the day. The mean temperature varies from 15°C to 20°C. Solar radiation at the study site is 1.3~1.9 times greater than that at Tokyo. These meteorological
conditions must be suitable for crop growth. Because of strong winds, as much as 10 m/s throughout the season, countermeasures using windbreaks have been taken.

Figure 3 compares the soil moisture characteristic curves of Guerrero Negro soil in the cabbage field with those of Tottori dune sand. The soil moisture-holding capacity after 24 hours and the depletion of moisture content for optimum growth for the Tottori dune sand are 8.5% and 2.8% of volumetric soil moisture content, respectively, while those for the soil at the study site in Guerrero Negro are 20% and 2.5% respectively. Thus, the available soil moisture at the study site is much larger than that of Tottori dune sand.

Water resources for irrigation at the study site depend on groundwater. Groundwater is pumped up from a depth of 30 m at the pumping station, which is 30 km from the study site. The groundwater is transferred by pipeline every day, and stored in a 100 m³ tank. This water is used for irrigation at the study site. The electrical conductivity of this water was 1.2 dS/m. This groundwater is also used for tap water in the town at the study site. The groundwater table at the study site is at a depth of about 4 m.

We do not have enough information to discuss the stability of the groundwater in the study area as an agricultural water resource. In this arid land, however, it is obvious that groundwater recharge due to rainfall at the site

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does not occur as described in the outline of the study site. Thus, in order to realize sustainable agriculture in harmony with the natural environment in this arid land, it is of great significance to develop irrigation technology adequate for saving water.

III. Materials and Methods

The crop used in this study is cabbage (Brassica oleracea Capitata, variety Copenhagen Market). Drip tubes having a length of 50 m were arranged in a line spacing of 0.84 m. One experimental treatment consists of three drip tube lines. The crop spacing is 40 cm.

Experiment 1 was performed for 80 days, from September 1, 1992, to November 19, 1992, and consisted of four treatments, T1, T2, T3, and T4, with different amounts of irrigation water. Experiment 2 had two treatments, T5, and T6, and ran for 104 days, from October 16, 1993, to January 27, 1994.

To determine the amount of irrigation water needed for maximizing crop yields, irrigation water $I$ is given as the product of the crop coefficient $k$ and potential evapotranspiration $ET_p$, which is calculated from the modified Penman method:

$$I = k \ ET_p$$  \hspace{1cm} (1)

The purpose of this study is to determine the value of $k$ in eq. (1) which gives the maximum yield of cabbage with minimum water use. The crop coefficient $k$ can be changed corresponding to the crop growth stages in order to
save water. However, data on irrigation water requirements for cultivating any vegetable in the arid desert of the study site are not available. In this study, the crop coefficient $k$ was assumed constant for all stages of cabbage development.

Drip irrigation is considered to be the most suitable way to save water when irrigation is frequent. Moreover, when soil moisture depletion around the soil surface is pronounced (see Figures 7 and 8), frequent irrigation is recommended because the roots near the soil surface may seriously affect the water-stress status. In general, soil moisture should be managed under high soil moisture conditions to avoid cracking of the cabbage head. Thus, in this study, continuous irrigation was introduced instead of intermittent irrigation. At the same time, it is desirable to determine the amount of irrigation water required on a daily basis. By taking into consideration the technical standards of the farmers at the study site, the amount of irrigation water was calculated on a weekly basis. This procedure is reasonable because meteorological conditions in the arid land of the study site change little during the course of a week.

To sum up, the amount of irrigation water for each treatment was determined by calculating the average value of the potential evapotranspiration ($ET_p$) of the previous week and then taking the product of $ET_p$ and the coefficient $k$ specified for each treatment. If rainfall was greater than the calculated amount of irrigation water, irrigation water was not applied. The validation of continuous irrigation will be discussed later, based on the micro total rapidly available moisture ($MTRAM$) and the measured data on soil moisture in the cabbage root zone.

Figure 4 shows the total amount of applied water, class A pan evaporation, potential evapotranspiration, and rainfall during experimental periods for experiments 1 and 2.
experiments 1 and 2. There was no rainfall during experiment 1, while 19 mm of rainfall was experienced during experiment 2 (with no irrigation on the day of the rainfall). The depth of applied water in Figure 4 was obtained from the depth of water in a wet area spreading from both sides of the drip tube on the soil surface. Figure 5 shows the soil surface after 24 hours and 48 hours of irrigation on the naturally dry soil surface under the conditions of irrigation intensity of 64 mL min$^{-1}$ m$^{-1}$ and the amount of 3.36 L m$^{-1}$ (about 11 mm). A wet width of about 30 cm can be recognized on both sides of the tube.

Table 1 shows the values of coefficient $k$ in eq. (1) given in the experiments.

Table 1 Values of the coefficient $k$ in each treatment.

<table>
<thead>
<tr>
<th>Coefficient $k$</th>
<th>Experiment 1</th>
<th>Experiment 2</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$T_1$</td>
<td>$T_2$</td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>1.3</td>
</tr>
</tbody>
</table>

After experiments 1 and 2 described above, a new experiment was conducted in March 1994 to investigate the relationship between potential evapotranspiration and soil moisture depletion associated with soil moisture uptake by cabbage roots after irrigation. Soil moisture was obtained using the heat probe method, in which soil moisture was calibrated from the measured thermal conductivity. The sampling time interval was one hour, and the sampling depths were 5 cm, 10 cm, 15 cm, and 20 cm. In this experiment, cabbage was transplanted at the same site as experiments 1 and 2 on February 1, 1994, and soil moisture was measured for three days beginning on March 15, 1994. Irrigation water was applied at 9:00 a.m. every day during this experiment. The irrigation intensity was about 64 L min$^{-1}$ m$^{-1}$, and the amount of irrigation water was obtained based on the results of experiments 1 and 2.
IV. Results and Discussion

1. Relationship between crop yield and coefficient \( k \)

Figure 6 shows the yield of cabbage with respect to the coefficient \( k \) in eq. (1) and also the value of the yield divided by total amount of irrigation water. The yield in this figure is that of commercial cabbage. Cabbage in which a fresh head weighs less than 0.8 kg and which thus has no commercial value is not included in the yield. For instance, because the average value of five heads of cabbage harvested in the field of treatment 1 of experiment 1 was 0.56 kg, this value was not included in the yield shown in Figure 6.

According to Figure 6, it can be said that a shortage of applied water leads to extremely low yields in treatments \( T_1 \) and \( T_2 \), while a nearly constant yield is obtained in treatments \( T_3 \sim T_6 \). The target yield of cabbage in Japan is about 45 t/ha. The yields in treatments \( T_3 \sim T_6 \) are lower than the target value. The reason for this is that the variety of Copenhagen Market studied usually has a smaller size, and the yield may be lower per hectare because of the drip tube spacing of 84 cm, which is wider than the normal spacing for cabbage cultivation. Generally, the size and mass of a fresh head of Copenhagen Market is 13~15 cm in diameter and 0.9~1.4 kg, respectively. The size and mass of cabbage harvested in this study are 14~18 cm in diameter and 1.0~1.8 kg (1.25 kg on average). These sizes and masses are greater than average. Thus, it can be said that the yield of the cabbage in treatments \( T_3 \sim T_6 \) is appropriate.

Crop yield tends to increase with crop transpiration. Transpiration is proportional to the amount of irrigation water for lower amounts of applied water, and yield increases with applied water. When irrigation water is

![Figure 6](image_url)

**Figure 6** Relationship between crop yield and coefficient \( k \), where \( k = I/ET_p \), \( I \) = irrigation, and \( ET_p \) = potential evaporation.

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increased, the yield tends to approach a constant value because excess water is not effectively used by the crop due to gravity drainage. Yields in treatments T3~T6 are approximately constant. Although overirrigation may exist in treatments T3, T4, and T6 in comparison with treatment T5, in which the ratio of yield to total applied water is maximum, the soil was not extremely wet.

Based on the results of Figure 6, the ratio of yield to applied water becomes maximum at \( k = 1.45 \) in treatment 5. Therefore, by choosing \( k = 1.45 \) in eq. (1), we can obtain high yields with the smallest amount of applied water. In this analysis, an amount of applied water is described using the depth of water in a wet area. The wet width was 30 cm and the drip tube spacing was 84 cm. The ratio between the wet width and the tube spacing is 0.3/0.84. Thus, the optimal crop coefficient, \( k = 1.45 \), obtained in this study can be converted to a value of about 0.5 based on the total cultivation area, which is obtained from \( 1.45 \times 0.3/0.84 \). To sum up, the adequate crop coefficient per total area of the field is 0.5.

2. Soil moisture dynamics in root zone

Figure 7 shows hourly changes in volumetric soil moisture content in the cabbage root zone from March 15 to March 18, 1994. Irrigation was started about 9:00 a.m. every day, and the amount of applied water was 1.45 times the daily average value of the potential evapotranspiration of the previous week based on the results of experiments 1 and 2. The cabbage roots were concentrated in the first 15 cm, and the maximum rooting depth found was about 18 cm. These observations suggest that the cabbage used in this experiment consumed water from the first 20-cm layer. Soil moisture up to 10 cm increases rapidly just after irrigation begins at 9:00 a.m., but changes in the soil moisture measured at 20 cm are small, even after the irrigation.

As shown in Figure 7, soil moisture at depths of 5 cm and 10 cm decreases
with time after irrigation. In particular, the soil moisture content at 5 cm decreases quickly, to about 2.5% after 17:00. In the soil moisture characteristic curve illustrated in Figure 3, soil moisture content of 2.5% corresponds to the point at which water is no longer available for optimum growth (pF 3). Even though the soil moisture content near the soil surface reaches the depletion level, it is likely that the cabbage is not under wilting conditions because the cabbage roots extract available water from the deeper soil layers. The changes in soil moisture around 20 cm are small because there are no cabbage roots. Thus the depth of 20 cm at which water was extracted due to the root water uptake, roughly coincides with the depth at which the soil moisture changes due to irrigation.

Figure 8 shows the vertical profiles of soil moisture before and after irrigation. Table 2 shows the average daily values of soil moisture depletion (SMD) up to a depth of 20 cm and the potential evapotranspiration $ET_p$ obtained for 2 days (March 15 and 16). It is difficult to obtain an accurate value of SMD in this experiment because of the small number of measurement points (4 points) in the vertical direction. Here we roughly estimate the SMD based on the measured values. The estimated value of SMD corresponds to the crop consumptive use on a daily basis by assuming that capillary rise from the lower layer is negligibly small.

Table 2 indicates that the value of SMD is about 1.5 times the potential evapotranspiration $ET_p$. When a crop coefficient $k < 1.45$ was selected in this

<table>
<thead>
<tr>
<th>Applied water (mm)</th>
<th>$ET_p$ (mm)</th>
<th>SMD (mm)</th>
<th>SMD/$ET_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.3</td>
<td>4.7</td>
<td>7.1</td>
<td>1.5</td>
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</tbody>
</table>

Table 2 Relationship between soil moisture depletion (SMD) and potential evapotranspiration ($ET_p$).
experiment, it could be observed from the soil moisture movement that a soil moisture deficit would occur since the amount of applied water does not meet the demand of the crop. The crop yield would decrease.

Based on the concept of micro total rapidly available moisture (MTRAM), the irrigation interval is discussed here. The moisture holding capacity after 24 hours of the soil in the cabbage field is 20% (in volumetric %). The soil moisture content for initiating irrigation is set at 5%, assuming that the initiating point for cabbage has the same pF 2.5 value as lettuce and celery. By setting a depth of 100 mm as the important soil layer for growth, the soil moisture consumption rate in this soil layer is 85%, based on the experimental results shown in Figure 8. These values result in $MTRAM = 17.6 \text{ mm}$. It is reasonable to suppose that the designed daily consumptive use value can be expressed by the maximum potential evapotranspiration of 7.5 mm (September 23, 1992) during the period of experiments 1 and 2. Hence, the designed value of optimal irrigation water is 10.9 mm, and the design irrigation interval is one day. Therefore the choice of continuous irrigation at the study site is reasonable.

V. Conclusions

Irrigation in the arid lands of the California peninsula, Mexico, is normally conducted using empirically based amounts of irrigation water. In this area, rainfed farming is not possible, and groundwater resources are finite. Thus, the evaluation of water requirements for drip irrigation is important step in saving water. The water requirement of drip-irrigated cabbage, $I$, was experimentally investigated taking into consideration the meteorological conditions and soil moisture dynamics at the sandy field in Guerrero Negro, which is located in the middle of the California peninsula, Mexico. The experimental results reveal that the crop coefficient $k = 1.45$, which means 1.45 times the potential evapotranspiration $ET_p$ calculated by the modified Penman method, leads to the optimal yield with the smallest amount of applied water. Therefore, $I = 1.45 \times ET_p$ can be considered as an adequate irrigation water standard for saving water at the cabbage study site. It was also shown that the daily soil moisture depletion in the cabbage root zone is about 1.5 times the potential evapotranspiration $ET_p$ on a day when the cabbage is growing under the irrigation water amount of 1.45 times the potential evapotranspiration of the previous week.

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References