IRRIGATION OF CROPS

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Recent research has provided new knowledge on managing irrigation water to decrease the degrading effects of irrigation on the mineral quality of drainage water and to increase crop yield and quality by effective use of sprinkler irrigation.

In sprinkler irrigation, water is exposed to the atmosphere, which enhances evaporation. The evaporation process cools the droplets, increases the heat absorbed by the droplets from the air through which they pass, and adds water vapor to the atmosphere. It has also been determined that the plant as well as its environment can be cooled with water applied by sprinklers.

Drainage water quality. The quality of drainage water from irrigated lands is influenced by the quality of the applied water, the leaching fraction (the fraction of the water infiltrating the soil and passing through it to become drainage water), the dissolving and precipitating of salts and minerals in the soil, soil properties, chemical amendments and fertilizers applied to the soil, and the removal of salts and minerals in crops. Recent research has increased the understanding of these factors. All natural irrigation waters contain some salts, and the quality of these waters for irrigation depends upon the total concentration and composition of the salts they contain.

Part of the water infiltrating the soil is removed in a pure state by evapotranspiration. Thus, the salts once contained in that fraction of the water are left behind and, except for the small quantity absorbed by plants, are concentrated in the water remaining in the soil. Much of this remaining water with its increased salt load will subsequently become drainage water reaching either ground or surface waters. Therefore, irrigating to produce crops increases the salt or mineral concentration in water and thus degrades the quality of water for subsequent uses.

Quality of applied water. The salt concentration in the irrigation water is a major factor influencing the salt concentration in drainage water that has percolated through the soil. Researchers at the United States Salinity Laboratory, Riverside, CA, have shown that the salt concentration of drainage water may vary about tenfold when a soil is irrigated with waters with a salt concentration range representative of typical western United States rivers. Concentrations of specific ions in drainage waters are also influenced by the concentrations of these same ions in the irrigation water.

When sufficient irrigation water was applied so that 0.1 of it passed from the soil as drainage water (leaching fraction = 0.1), the salt concentration in the drainage water was about six times that in the original irrigation water as measured by electrical conductivity, or EC (Table 1), except for the purest irrigation water (EC = 0.10) for which the increase was much greater. Much of the drainage water from irrigated lands returns to rivers and, after mixing with river water, is reused to irrigate lands downstream. Each time water is reused for irrigation, its salt concentration is greater than when it was used before, and each time more salt is picked up as the water passes through the soil and the salt concentration increases in the drainage water. Thus, in irrigated areas the mineral quality of river waters decreases downstream from the first irrigation project. In the lower reaches of some rivers, the quality of the water is so poor that the water is not suitable for irrigation.

Leaching fraction. The fraction of water infiltrating the soil and appearing as drainage water is known as the leaching fraction. It approximates the amount of water applied in excess of evapotranspiration requirements. Some leaching is required to avoid salt accumulation to a concentration harmful to growing plants. The leaching fraction influences both the salt concentration in the drainage water and the total salt output from irrigated land. When the leaching fraction is increased from 0.1 to 0.3, the salt concentration in the drainage water is decreased (Table 1). However, the threefold increase in the leaching fraction results in less than a threefold decrease in the drainage water salt concentration. This means that the total salt output from irrigated land generally increases as the leaching fraction increases. For a 203,000-acre irrigated tract in southern Idaho with a leaching fraction of 0.5, the salt concentration in the drainage water was 2.26 times that in the irrigation water. If the increase in salt concentration had resulted only from evapotranspiration, the increase would have been 2.0 times. The additional increase of 0.26 times arises from dissolving minerals in the soil, and perhaps other factors.

Table 1. Influence of the salt concentration in irrigation water and the leaching fraction on the salt concentration in drainage water of soils containing $CaCO_3$*

Irrigation water†	Leaching fraction	Drainage water†
0.10	0.1	1.84
0.10	0.2	1.45
0.10	0.3	1.17
0.91	0.1	5.66
0.91	0.2	3.12
0.91	0.2	2.65
1.27	0.1	7.27
1.27	0.2	4.56
1.27	0.3	3.59
3.26	0.1	17.72
3.26	0.2	9.63
3.26	0.3	8.30

*Data from J. D. Rhoades et al., in *Proc. Soil Sci. Soc. Amer.*, 37:770–774, 1973.

†Salt concentration is measured by electrical conductivity in mmhos/cm.

Recent research results indicate that the leaching fraction should be kept as low as possible to prevent salts from concentrating in the soil and harming plants, because the lower the leaching fraction, the lower the total salt outflow and the less the subsequent mineral quality degradation of surface and groundwaters.

Salts and minerals in soil. Some soils contain deposits of soluble salts resulting from geologic and climatic processes. When irrigation water flows through soil with such salt deposits, large quantities of salts dissolve, and drainage water from such soils has an extremely high salt concentration. Also, many soils in arid areas contain enough soluble salt so that drainage waters during the first few years of irrigation contain high salt concentrations. Later, as these salts are leached out of the soil, the salt concentration in the drainage water decreases.

Some salts such as sodium chloride (NaCl) are highly soluble, others such as gypsum ($CaSO_4 \cdot 2H_2O$) are sparingly soluble, and still others such as lime ($CaCO_3$) are only slightly soluble. Also, some soil minerals are more soluble than others. Therefore, large quantities of salt are leached from some soils and only small quantities from others. For example, 12 tons of salt per acre each year is carried by drainage water into the Colorado River from a study area in the Grande Valley, CO. In contrast, only 1 ton per acre per year was leached from a large tract in southern Idaho.

Soil properties. Many processes take place in irrigated soils, including exchange reactions involving salinity ionic components, oxidation and reduction reactions, and pH changes. These processes all influence the salt concentration in drainage water. Some soils contain $CaCO_3$, which controls pH and many soil reactions in the soil, which in turn influence the quality of drainage water.

Chemical amendments and fertilizers. The application of chemical amendments, such as lime or gypsum, can markedly influence the salt concentration and composition of drainage water. Applying such amendments can increase water infiltration, change soil aeration, and supply ions for exchange processes. All of these factors influence the quality of drainage waters. Similarly, fertilizers can influence drainage water quality, although their effects are usually small because relatively small quantities are applied. Nitrogen fertilizers can influence the nitrate concentration in drainage water if sufficient water is applied to leach some of the fertilizer through the soil. *See* SOIL.

Removal of salts and minerals in crops. Growing plants absorb small amounts of various minerals supplied by the soil, the irrigation water, or applied fertilizers. In most irrigated areas, the amount of mineral salts removed by plants represents such a small fraction of the total salt in the soil that its influence on drainage water quality can be neglected. Only when irrigation water contains an unusually low salt concentration does this factor have a significant effect, which would be lowering the salt concentration in the drainage water.

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Changes in plant microclimate. The increase in atmospheric vapor pressure and decrease in air temperature in sprinkler irrigation are of interest in crop production, because significant changes in these microclimatic variables could either benefit or retard plant growth, depending on existing weather conditions and plant environmental requirements. Under warm weather conditions, growth of cool-season crop might be improved, but growth of a warm-season crop might be retarded. Changes in air temperature above the crop will not be large, however, usually less than 1°C downwind from a sprinkler line.

Evaporation processes. Changes in vapor pressure and air temperature just above the crop surface depend directly on the amount of water evaporated. Generally, the total evaporation includes the evaporation from the spray plus that from the wetted foliage and transpiration. Wetted-foliage evaporation under sprinkler irrigation has been studied with fully established forage crops under arid conditions. The results showed that evapotranspiration from the wetted foliage was approximately equal to that from nonwetted, actively growing foliage when the crop had adequate soil moisture. Therefore, the influence of sprinklers on air temperature and vapor pressure over a well-watered crop would be mainly from spray evaporation.

The relatively short time of flight of the water droplets from nozzle to crop surface (usually less than 2 sec) and the very small volume of air in contact with the disintegrating jet severely limit the amount of heat that can be absorbed. Thus, a relatively small amount of evaporation occurs. Both I. Seginer and F. Robinson found that under arid conditions spray evaporation loss was less than 5% of the water discharged from standard agricultural sprinklers. At wind speeds of 2 to 3 m/sec, a 6% evaporation loss should reduce temperature 1°C or less and increase vapor pressure about 0.5 mb in the 1- to 2-m zone above the crop.

Downwind effects. R. Kohl and J. Wright measured the changes in air temperature and vapor pressure downwind from an operating sprinkler lateral under the semiarid conditions of southern

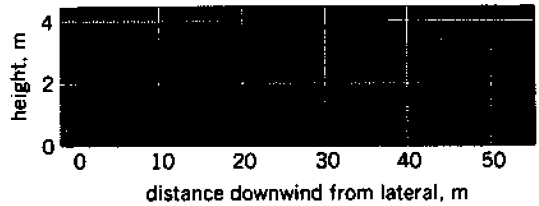

Fig. 1. Dry-bulb temperature depression downward from an operating sprinkler lateral. *(From R. A. Kohl and J. L. Wright, Air temperature and vapor pressure changes caused by sprinkler irrigation, Agron. J., 66(1):85–87, 1974)*

Idaho. They found that the air temperature was generally reduced less than 0.6°C. Figure 1 illustrates the degree of cooling found downwind from an operating sprinkler lateral.

The reduction in atmospheric cooling with elevation and distance downwind results from rapid vertical mixing by eddy diffusion. The magnitude of the changes in the horizontal direction is not expected to increase much with reduced wind speed, since strong vertical mixing exists under such conditions during the summer daylight hours.

For the most part, the addition of evaporated water vapor to the air passing through the spray is an adiabatic process. Adiabatic evaporation reduces the dry-bulb temperature and increases the vapor pressure, but does not change the wet-bulb temperature. Experimental data indicated that the wet-bulb temperature did not change significantly since the increase in vapor pressure due to spray evaporation was less than 0.8 mb.

As a rotating sprinkler applies water from a jet, at a given instant the droplets contact a very small portion of the air volume in the first 2 m above the crop. Therefore, a large change in temperature and vapor pressure from a single operating lateral cannot be expected.

Usually the magnitude of these changes is less than the modification in temperature and vapor pressure near the ground as dry air passes over an actively growing, well-watered crop. D. DeVries and J. Birch, comparing irrigated and dryland pastures in Australia, found temperatures 1 to 2°C lower, and vapor pressures 0.7 to 2.0 mb higher at the 1.25-m height 1 to 5 km inside the irrigated land. Thus, an actively transpiring crop significantly changes the microclimate in its vicinity because of the evaporative cooling process taking place over a large area.

Since the effect of an operating sprinkler lateral is dissipated downwind by vertical mixing, evaporative cooling within an irrigated area has a greater influence on air temperature and vapor pressure than a few sprinkler laterals. However, the effect of evaporative cooling resulting from sprinkler water evaporating from plant foliage is another subject and can be significant. [R. A. KOHL]

Changes in plant temperature. Significant advances have been made in predicting changes in plant, air, and soil temperature that result from evaporative cooling. Some reported increases in yield and quality attributed to lowering plant temperature by mist irrigation may not have been directly due to cooling, but to improved irrigation water management. Some studies in moderate climates show that misting and consequent lowering of plant and soil temperatures lowered yield and quality of some crops.

Mathematical models. Mathematical models are available to predict the change in plant temperature under various environmental conditions. Except for short periods of time, plants exposed to full sunlight seldom are at the same temperature as the ambient air. The plant temperature is in balance with the dissipation of heat energy that is absorbed. Plant surfaces gain heat from solar radiation and lose it by long-wave radiation to the atmosphere and the soil surface, by evaporation which converts sensible and radiant heat energy to latent heat, and by photosynthesis which converts a small amount of radiant energy to chemical energy. Mathematical models of leaf temperature show that leaf temperatures increase as the direct angle of the sun increases, and decrease with the square root or $\frac{2}{3}$ power of wind speed and the rate of transpiration. The temperature of the wetted portion of the plant cannot decrease below the psychrometric wet-bulb temperature, which is related to relative humidity and air temperature (Table 2).

Leaf temperature. Under arid conditions with low relative humidity when the saturation deficit (the difference between saturation vapor pressure and the actual vapor pressure in the air) is high, leaf temperatures tend to be lower than air temperature for several days after a thorough irrigation. As soil moisture decreases, the difference between leaf temperature and air temperature decreases. When most of the soil water has been depleted, leaf temperature may exceed air temperature. Under humid conditions the saturation deficit is usually relatively low. Under these conditions leaf temperatures are often 5 to 10°C above ambient air temperature and increase as available soil moisture decreases. The temperature of leaves drops very rapidly when wetted. Potato and cotton leaves decrease 10 to 12°C when wetted, but within 10 to 15 min generally return to the original temperatures as the water on the leaf surfaces evaporates. Since leaves of most farm crops are very thin, they have a large surface area per unit of mass. Heat gained from solar radiation is lost by transpiration, reradiation, and convection. Convection is closely related to wind speed and tends to dominate leaf temperatures when soil moisture is adequate.

Bud temperature. Plant components such as the buds on fruit trees and small stems have a relatively small surface area per unit mass. When they are wetted by sprinklers, they tend to approach the wet-bulb temperature, especially in the spring when solar radiation is low. J. Alfaro and coworkers used automatic sprinklers which operated when air temperature exceeded 5°C to keep the buds wet during the daytime hours. The wetted buds remained below air temperature and near the wet-bulb temperature during the day. By wetting the buds, their development is delayed and the probability of damage due to late spring frost when the trees would normally be in full bloom is reduced.

Table 2. Relationship of relative humidity to air temperature and wet-bulb temperatures for wetted portions of plant

Relative humidity, %	Wet-bulb temperature, °C, at air temperature of: 20°C	30°C	40°C
20	9	16	22
40	12	20	28
60	15	24	33
80	18	27	37

Cooling fruit. Overhead sprinkler irrigation has been used for many years to cool fruit such as apples, pears, and avocados. C. Unrath found that apples exposed to the sun in North Carolina often reached temperatures 8 to 11°C higher than air temperature, when air temperature exceeded 30°C. Misted fruit was 3 to 5°C cooler than air during the same period. Automatically activating the sprinkler system when temperatures exceed 30°C improved the quality of the apples by increasing the area of solid red color. Misting pears decreased their core temperature about 8°C. Prunes exposed to the sun were cooled 6 to 8°C when sprinkled, but shaded fruit was not affected as much.

Vineyards. Air temperatures often exceed 30°C and may reach 40 to 45°C in the San Joaquin Valley of California. Sprinkling vineyards using solid set sprinklers when temperatures exceed 30°C lowered air temperatures 4 to 6°C. The bulk of the temperature decrease occurred within the first 3 min. In about 15 min, leaf temperatures were about the same as before sprinkling. Leaf petiole temperature was decreased 8 to 14°C by sprinkling, and grape berry temperature was decreased 6 to 11°C. Sprinkling tended to lower the sugar content and increase the total acid, which suggested that sprinkling delays maturity and harvest date.

Effect on potatoes. In Minnesota, mist irrigation on potatoes decreased air temperatures within the canopy as much as 5 to 10°C in the upper part and 15 to 20°C in the middle part. The effect on growth and development, however, resulted in more small tubers of lower quality.

Optimum temperatures. Results to date indicate that evaporative cooling has been used to reduce apparent temperature stress when the plant may not have been adversely affected by the moderate temperatures under some conditions. Studies by K. Krogman and W. Torfason indicate that, if potatoes are adequately irrigated, misting the plant to lower the leaf temperatures has no beneficial effect. Optimum plant growth temperatures are needed, as are temperatures at which detrimental effects may occur within the leaf, flower, fruit, or other portions of the plant. Recent studies by C. Tanner and S. Goltz indicate that very high temperatures can occur in seed onion umbels. Excessively high temperatures produce sun scald, with desiccated and aborted florets on the sunlit side of the umbels. An umbel has few stomata, and consequently, its temperature is strongly regulated by convective heat transfer. In Wisconsin, umbel temperatures may exceed air temperature by as much as 25°C at wind speeds between 50 and 100 cm/sec, but only about 10°C at wind speeds of 250 to 350 cm/sec.

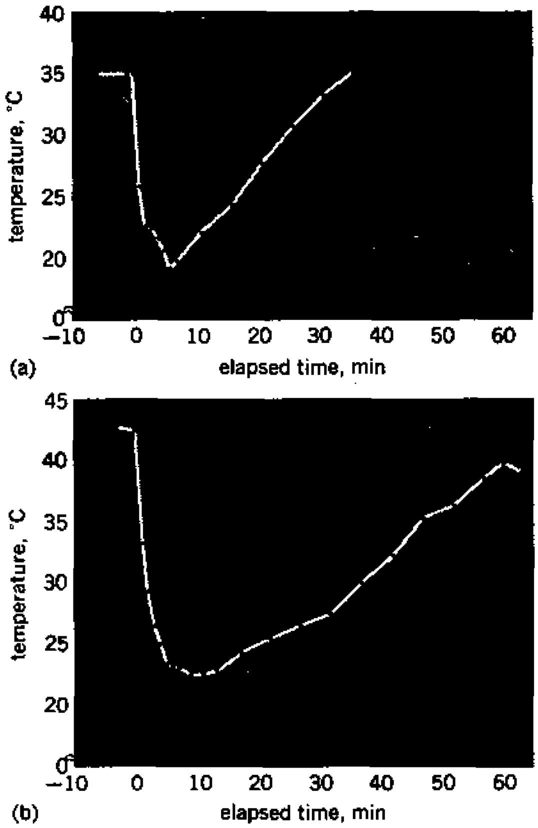

Fig. 2. Temperature of open florets in an onion umbel that has been wetted by sprinkler-applied water in Kimberly, ID. *(a)* Temperature changes that occur with moderate wind speeds; *(b)* changes that occur with low wind speeds. *(Unpublished data of J. L. Wright, J. L. Stevens, and M. J. Brown, ARS, Kimberly)*

Figure 2 shows that because of the ability of the seed head to retain water, sprinkling the onion umbel can reduce floret temperatures as much as 20°C and their temperatures will remain below air temperatures for about 20 to 40 min. With moderate wind speeds, the temperature of open florets was 5°C above air temperature and sprinkling lowered it 15°C. The temperature returned to ambient air temperature in about 25 min. With low wind speeds, open floret temperature was about 10°C above air temperature and the misted umbel remained below air temperature for about 40 min.

Evaporative cooling to enhance the quantity and quality of crop production has many possibilities. However, optimum temperature must be delineated and maintained relative to other microclimate conditions. Also economic systems must be developed to automatically control and supply small amounts of water frequently throughout the day when air temperatures exceed critical levels.

For background information *see* IRRIGATION OF CROPS; LAND DRAINAGE (AGRICULTURE); PLANT, WATER RELATIONS OF in the McGraw-Hill Encyclopedia of Science and Technology.

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Bibliography: J. F. Alfaro et al., *Preventive Freeze Protection by Preseason Sprinkling to Delay Bud Development*, ASAE Pap. 73-2531, 1971; C. A. Bower, in J. van Schilfgaarde, ed., *Drainage for Agriculture*, chap. 17, 1974; D. L. Carter, C. W. Robbins, and J. A. Bondurant, *Agricultural Research Service Publ. ARS-W-4*, 1973; D. A. DeVries and J. W. Birch, *Austr. J. Agr. Res.*, 12:260–262, 1961; R. A. Kohl and J. L. Wright, *Agron J.*, 66(1): 85–87, 1974; K. K. Krogman and W. E. Torfason, *Amer. Potato J.*, 50(4):133–137, 1973; J. D. Rhoades et al., in *Proc. Soil Sci. Soc. Amer.*, 37: 770–774, 1973; F. E. Robinson, *Agron. J.*, 65:130, 1973; I. Seginer, *Agr. Meteorol.*, 4:281–291, 1966; G. V. Skogerboe and W. R. Walker, *J. Environ. Qual.*, 2:377–382, 1973; C. B. Tanner and S. M. Goltz, *J. Amer. Hort. Sci.*, 97(1):5–9, 1972; C. R. Unrath, *J. Amer. Hort. Sci.*, 97(1):58–61, 1972.