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# Advection and Evapotranspiration of Wide-Row Sorghum in the Central Great Plains[1]

R. J. Hanks, L. H. Allen, and H. R. Gardner[2]

**ABSTRACT**

**This study was conducted to evaluate the importance of advection as a source of energy for evapotranspiration from grain sorghum planted in 1-m rows with both irrigated and dryland conditions. Detailed measurements of temperature, water vapor content, and wind speed were made within and above the canopy at various times and positions within the field during August 1967. Evapotranspiration was also measured by soil moisture sampling. Three types of advection were observed. Within-canopy advection resulted from the large amount of exposed dry soil between rows, which caused soil temperature between the rows to be as much as 20 C higher than plant temepratures. About 64% of the energy used to heat up the soil was used for transpiration in the irrigated plot, whereas only about 21% of the energy was used for transpiration in the dryland plot. Border advection, manifested by horizontal temperature and water vapor gradients, occurred over most of the plot irrigated but was most evident from 0 to 40 m from the upwind edge. This type of advection yielded sufficient energy to account for about 30% of the energy used for evapotranspiration from the irrigated plot. Large scale advection, manifested by temperature inversions, was found to occur during the night and probably yielded very little energy used for evapotranspiartion.**

***Additional index words:*** **Microclimate, Edge-effect.**

IN water-deficient areas, such as the Central Plains, advection of heat from surrounding areas may be an important source of energy used in evapotranspiration from crops. Large areas of fallow prevail where evaporation is much less than the net radiation input. Some of the excess energy from fallow areas is advected to adjacent cropped areas. Native grass, which is predominant in the region, is another source of advective energy for a large part of the season. Most field crops are deeper rooted than native grass and grow only part of the year. Therefore, the water supply to crops during the active period of growth is sufficient to maintain higher evapotranspiration rates than the surrounding native grass or fallow. Under these conditions, as reported by Hanks et al. (1968), advection may be a significant source of energy used for evapotranspiration on cropland. It was also apparent that evapotranspiration relative to pan evaporation was highly dependent on the crop.

Abdel-Azis et al. (1964) measured evapotranspiration by alfalfa near Logan, Utah, during July and August, using the neutron soil moisture probe method. They found that more water was used than was estimated by the Penman formula. They also found that evapotranspiration exceeded class A pan evaporation when the crop was tall and water was plentiful, but that it was less than class A pan evaporation after the field was cut and/or soil moisture was limiting. They attributed the evapotranspiration to heat advection and surmised that much of it occurred at night when the winds were highest. Rosenberg (1969a, 1969b) used lysimetric methods to show that evapotranspiration of 25-cm high alfalfa at Mead, Neb., exceeded available radient energy by as much as 85%. His nighttime evapotranspiration rates were small. They averaged about 0.075 cm/day of water, or about 10% of total evapotranspiration. This may have been partly due to low wind speed and low temperature (skidmore et al., 1969) or to stomatal closure in the dark. Van Bavel and Ehrler (1968), using lysimeters, showed that advected heat supplied much of the energy used for transpiration from a well-watered dense (leaf area index = 4.2) grain sorghum crop. They measured low evapotranspiration rates at night (about 6% of total) because of stomatal closure.

Penman et al. (1967) have reviewed the literature on the influence of advection on evaporation and transpiration. They conclude that where advection is important, local influences may be so great that any general relationships for estimating evapotranspiration may have to be modified by local research.

The purpose of this experiment was (*1*) to evaluate the importance of advection as a source of energy for evapotranspiration by grain sorghum planted in 1-m rows, and (*2*) to compare the effects of water supply (irrigation) and meteorological condition on the partitioning of incoming solar energy into latent heat and sensible heat components. This report is part of a larger study by Hanks et al.[3]

[1] Contribution from the Northern Plains Branch, Soil and Water Conservation Research Division, Agricultural Research Service, USDA. Received June 10, 1970.

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[3] Hanks, R. J., H. R. Gardner, L. H. Allen, J. T. Woolley, W. R. Gardner, L. J. Fritschen, E. R. Lemon, and J. K. Aase. 1970. Soin-plant-water microclimate relations of wide row grain sorghum in the Central Great Plains. USDA, SWCRD, ARS-41- (In press)

## PROCEDURE

The experiment was conducted at the USDA Central Great Plains Experiment Station near Akron, Colo., in 1967. A general description of the area was given earlier by Hanks et al. (1968). Two plots were studied (Fig. 1). The irrigated plot was 92 m (E-W) by 137 m (N-S). The dryland plot was 115 m (E-W) by 137 m (N-S). Grain sorghum (*Sorghum bicolor*, var. 'RS-610') was planted on June 19 in 1-m wide, east-west rows. The number of plants per meter of row averaged 9.0 in the irrigated plot and 8.0 in the dryland plot. A fallow field extended about 1000 m to the north and west. A nearby cropped area was on the east side. A low highway and a railroad were on the south side, with grassland beyond. The wind direction in the area was usually southerly or northerly. Wind speed and wind direction were recorded continuously using a single rotating-cup anemometer and a wind vane. These instruments were located at a height of 2 m above ground about 15 m south of the northern edge of the dryland plot. Hygrothermograph data were also recorded continuously in a standard weather shelter.

A neutron probe was used throughout the season to measure moisture depletion and evapotranspiration from the soil of the plots. Measurements were made at 30-, 60-, 90-, 120-, 150-, and 180-cm depths at six sites in each plot near L-1, L-3, and L-5 and near L-6, L-8, and L-10.

Net radiation measurements above the vegetation were made using instruments described by Fritschen (1965b). Three net radiometers were located near L-1, L-3, and L-5 in the irrigated plot and three more near L-6, L-8, L-10 in the dryland plot. In addition, net radiation penetration into the plant canopy was measured at heights of 5, 20, 40, 60, and 100 cm using a motorized radiometer traversing system. Eight runs in each plot were made at selected times during late August and early September.

Soil heat flow was measured at the same locations as net radiation, using heat flow plates similar to those described by Tanner (1963). Two plates were wired in parallel at each location. The plates were buried about 5 cm deep and were located about 25 cm north of the row.

A sweeping-boom aspirated sampling system similar to that of Fritschen (1965) was used to measure air temperature and

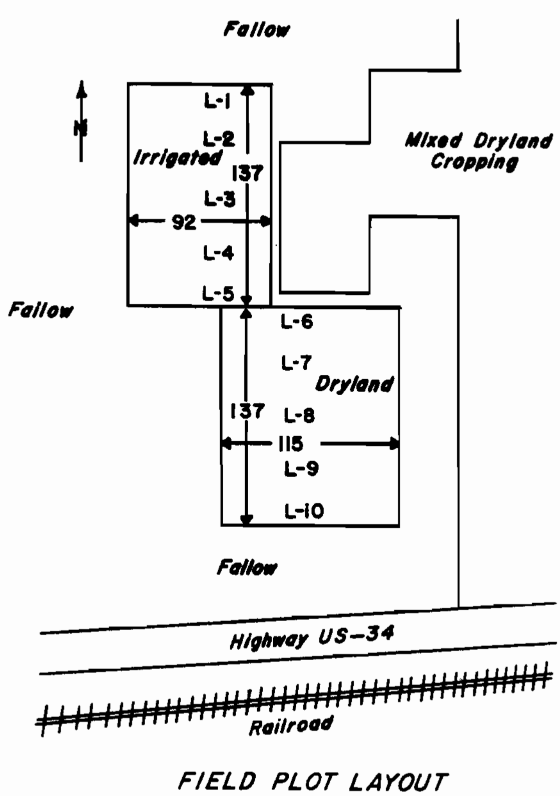


**Fig. 1. Field plot layout. L-1 to L-10 are the lysimeter locations. Dimensions are in meters.**

water vapor concentration gradients at three locations over the irrigated plot. These gradients were used to compute evapotranspiration by the energy balance — Bowen ratio method. Measurements were made at a height interval of 30 cm, with the lower sampling inlet about 15 cm above the crop. Thermocouples were used to measure temperature gradients and LiCl dew cells to measure water vapor gradients. The upper and lower air intake ports reversed positions every 15 minutes. Net radiation, soil heat flow, temperature gradient, and water vapor concentration gradient data from these instruments were automatically recorded every 15 minutes on a Howell[4] millivolt (— 2 to + 18 mv) digital print-out recorder. The results reported are averages from the three locations in the plot.

In addition to the Bowen ratio measurements, 10-level profile measurements were made of water vapor concentration, air temperature, and wind speed at 5, 20, 40, 60, 80, 110, 130, 170, 250, and 410 cm. Seventy of these simultaneous, short-term profiles obtained from August 16 to August 30. Wind speed and air temperature also were measured at 330 cm. The mean profile data reported are average values obtained over a 10- to 15-minute sampling period.

To obtain water vapor concentration, about 8 liters of air were pumped simultaneously from 10 heights through 0.6-cm (¼-in.) copper tubing and stored in special bags (inner layer of polyethylene, middle layer of aluminum foil, and outer layer of mylar). The bags were transported to a laboratory, where the water vapor concentration was measured using a "moisture analyzer" manufactured by DuPont[4]. The air temperature profiles were obtained with aspirated, radiation-shielded, 5-junction thermopiles. The bottom level was referenced against an ice bath. Temperature differences were measured between successive heights and were used to calculate the air temperature profile. Wind speed above the crop (110 to 410 cm) was measured with sensitive rotating-cup anemometers. Wind speed from 5 to 110 cm was measured with inverted Hastings-Raydist[4] heated-thermocouple anemometers.

Custom-built instruments (Assmann psychrometer type) were used to measure the horizontal variation of air temperature and water vapor concentration. These measurements were made with five portable radiation-shielded, aspirated, mercury-in-glass thermometer units that measured the wet-bulb and dry-bulb air temperature. Readings were made at five locations across the plot at a given height simultaneously by five people. Some runs were made with one site in the fallow 7 m upwind from the plot border. One minute was allowed at each height for the instrument to come to equilibrium before readings were made and the instrument was raised to the next height. Data were taken at 5-, 20-, 40-, 60-, 80-, 110-, 130-, 170-, and 250-cm heights several times a day from August 21 to August 25. Comparison of the five units showed agreement to about 1 C.

Table 1 gives precipitation and irrigation during the 1967 growing season. This was a wet season with 32.4 cm of rainfall between May 29 and the last heavy rainfall on July 12. Only 0.12 cm of rain occurred during the days of intense micrometeorological measurements (August 16 to August 29).

All times are reported in Mountain Standard Time. Solar noon occurred at about 1140. Further details of the procedure and other studies made are given by Hanks et al.[3]

[4] The suppliers names are listed for convenience of the reader and do not constitute a guarantee or warranty by the U. S. Department of Agriculture of products names nor an endorsement by the U. S. Department of Agriculture over other products available on the market.

**Table 1. Summary of precipitation and irrigation at Akron, Colo., April 20 to September 12, 1967. The irrigation for August 5 and August 12 assumes 0.80 cm evaporation.**

| Date | Cummulative precipitation | Irrigation | Cummulative irrigation plus precipitation |
|---|---|---|---|
| | cm | cm | cm |
| Apr. 20 to May 22 | 5.21 | -- | 5.21 |
| May 25 | 5.21 | 4.46 | 9.87 |
| May 26 to June 15 | 21.40 | -- | 26.06 |
| June 19 | 21.40 | Grain sorghum planted | |
| June 21 Aug 1 | 38.74 | -- | 43.40 |
| Aug 5 | 38.74 | 4.05 | 47.45 |
| Aug 9 | 38.76 | -- | 47.47 |
| Aug 10 | 38.76 | 3.44 | 50.91 |
| August 16 to August 29 | 38.86 | -- | 51.01 |
| August 16 to September 12 | 40.27 | -- | 52.42 |

## RESULTS

The leaf area index measured on August 21 and August 28 averaged 1.165 for the irrigated plot and 0.814 for the dryland plot. The fractional distribution of the leaf area index for the irrigated plot was 0.002, 0.078, 0.472, 0.375, 0.069, and 0.002 for the 0 to 5-, 5 to 20-, 20 to 40-, 40 to 60-, 60 to 80-, and 80 to 100-cm height intervals respectively. The fractional distribution of the leaf area index for the dryland plot was 0.000, 0.042, 0.381, 0.483, 0.093, and 0.001 for the same height intervals, respectively. The approximate crop height increased from 66 cm (irrigated) and 61 cm (dryland) on August 16, to 76 cm (irrigated) and 68 cm (dryland) on August 25. After August 25 seed heads appeared so that plant height had increased by 21 cm (irrigated) and 18 cm (dryland) by August 29. Ground cover, estimated from photographs, was 38% on August 16 and 40% on August 28.

Net radiation, $R_n$, soil heat flow, S, and evapotranspiration, ET, for several days in August are shown in Table 2. The days were mostly clear except for August 18 which had large cumulus clouds during the day and August 22 which had dense cirrostratus clouds in the west after 1400 MST. ET obtained by neutron proble sampling is assumed to describe water use by the plots as a whole. The table shows that sensible heat flux density A ($A=R_n-S-ET$) was slightly positive for the dryland plot. This result indicates that on a long-term basis that there was a net transfer of heat to the air above the dryland plot, and hence that no net advected energy was used for ET. However, advected heat supplied about 0.3 of the energy used in ET for the irrigated plot. ET computed by the energy balance-Bowen ratio equation using the sweeping-boom sampling system showed no advection.

Three scales of advection were measured in this experiment. Large scale advection occurred because of vertical temperature inversions. Border advection occurred because of horizontal temperature and vapor pressure gradients, especially near the plot edge. Within-canopy advection occured because of the large amount of dry soil exposed between the rows which caused soil temperatures to be higher than plant temperatures. These three scales of advection will now be discussed in detail.

**Table 2. Net radiation ($R_n$), soil heat flow (S), evapotranspiration (ET), heat flux to the air (A), incoming solar radiation ($R_s$), mean wind speed at 410 cm (U), maximum temperature (Tm), and mean relative humidity (RHm) for several days in August 1967 at Akron, Colo. The value of ET, $R_n$, and S are expressed as equivalent cm/day (cm = 580 cal). ET from the neutron probe and lysimeter data are the daily averages from August 15 to August 28.**

| | Irrigated | | | Dryland | | Ambient | | | |
|---|---|---|---|---|---|---|---|---|---|
| Date | Rn | S | ET (com)* | Rn | S | U, cm/sec | Tm, °C | RHm, % | Rs, ly/day |
| August 16 | 0.50 | 0.14 | 0.30 | 0.49 | 0.10 | 277 | 32.2 | 16 | 560 |
| 18 | 0.47 | 0.09 | 0.29 | 0.45 | 0.06 | 730 | 24.4 | 44 | 545 |
| 21 | 0.51 | 0.18 | 0.28 | 0.46 | 0.14 | 226 | 32.2 | 15 | 553 |
| 22 | 0.43 | 0.14 | 0.29 | 0.39 | 0.10 | 299 | 32.2 | 20 | 500 |
| 23 | 0.53 | 0.16 | 0.27 | 0.46 | 0.12 | 298 | 32.8 | 18 | 505 |
| 24 | 0.52 | 0.13 | 0.26 | 0.46 | 0.10 | 496 | 35.6 | 15 | 506 |
| Avg. | 0.49 | 0.14 | 0.28 | 0.45 | 0.10 | | | | |
| ET (neutron probe) | 0.51 cm/day | | | 0.32 cm/day | | | | | |
| A = Rn-S-ET (neutron probe) | -0.16 cm/day | | | 0.03 cm/day | | | | | |
| Evap (BPI pan) | 0.64 cm/day | | | | | | | | |

* ET (com) = $\frac{Rn-S}{1+\beta}$, where $\beta$ is defined by equation [1]. Measurement made using sweeping boom sampling system (Fritschen, 1965).

Large-scale advection was measured, but its importance is not known. This type of advection is fairly common as discussed by Penman et al. (1967) and Rosenberg (1969a, 1969b). This type of advection is the only kind that can be sensed by the energy balance–Bowen ratio equation because there has to be a temperature inversion above the crop. The measurements made by the 10-level air temperature mast indicated inversions occurred only in the late afternoon, after the atmosphere generally had heated up and the radiation load on the plants had started decreasing, or under cloud cover. Based on this information alone we at first concluded that advection would not be significant. However, a closer examination of the temperature gradients made on a continuous day and night basis by the sweeping-boom Bowen ratio apparatus revealed temperature inversions to occur from late afternoon until the next morning. Table 3 shows the time intervals when inversion occurred.

Temperature inversions over the irrigated plot recurred fairly consistently from about 1500 MST in the afternoon to about 0700 MST the next morning. Most of this time $R_n-S$ was very nearly zero. This caused computed ET to be nearly zero regardless of the value of $\Delta T$ or $\Delta E$. Some ET probably occurred at night because there was a measurable gradient of water vapor.[3] Most of the potential for large scale advection would occur a night, a time when the energy budget–Bowen ratio method is subject to the most error, as discussed by Fritschen (1965a). A significant part of ET during the night was probably evaporation from the soil. Leaf porometer data and silicone rubber stomata impressions indicated that the stomata were closed at night (data of J. T. Woolley in Hanks et al.[3]). A large heat load averaging 0.25 equivalent centimeters of water for the days of Table 2 went into soil heat during the daylight hours.

Evidence of the importance of border advection (clothes-line effect) was observed on several days. This type of advection has been reported by many others for many different circumstances (Bradley, 1965 and 1968; Brooks, 1961; Glaser, 1955a and 1955b; Rider et al., 1963). Air temperature and vapor pressure obtained from measurements of wet bulb and dry bulb temperatures are shown in Fig. 2, 3, and 4. The data for August 22 (Fig. 2, irrigated) and August 24 (Fig. 3, dryland) show the effect of the air moving from fallow into cropped region. The data from the nine sampling heights were grouped to simplify the figure and to reduce variability.

The prominent effect of Fig. 2 and 3 is the sudden increase in temperature from the fallow to a location 7 m inside the plots. This effect is due to the horizontal convergence and concomitant vertical diverg-

**Table 3. Time intervals when temperature inversions prevailed. Time is Mountain Standard Time. Akron, Colo., 1967.**

| Start | End |
|---|---|
| 8-16 1515 | 8-17 0500 |
| 8-17 1345 | - |
| 8-18 1745 | 8-19 0315 |
| 8-21 1530 | 8-22 0800 |
| 8-22 1315 | 8-23 0600 |
| 8-23 1530 | 8-24 0800 |
| 8-24 1515 | 8-25 0500 |
| 8-25 1500 | 8-26 0615 |

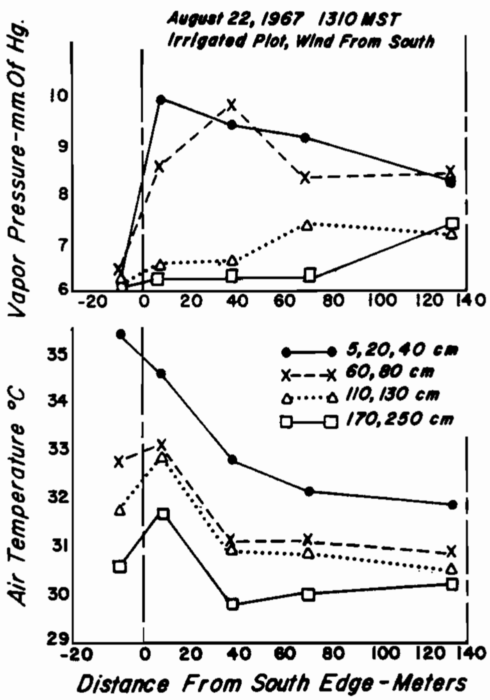


Fig. 2. Air temperature and vapor pressure as a function of height and distance from the south edge of the irrigated plot (upwind) on August 22, 1967 at 1310 MST.

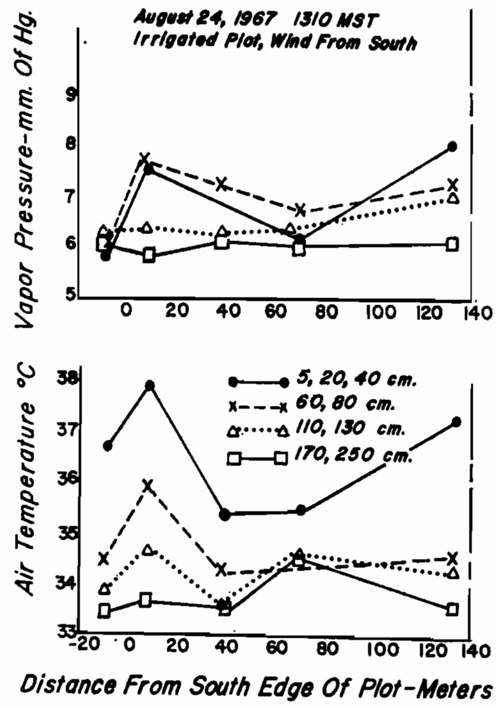


Fig. 3. Air temperature and vapor pressure as a function of height and distance from the south edge of the dryland plot (upwind) on August 24, 1967 at 1300 MST.

ence of wind as it blows from the relatively smooth fallow to the relatively rough grain sorghum. Kutzbach (1961) and Stearns and Lettau (1963) demonstrated convergence and divergence of flow in controlled roughness field experiments. Fig. 5 shows the effect of the wind speed profile as air moves from fallow to the crop plot. Real normalized wind speed profiles are shown for 20-m, 71-m, and 102-m fetches. The leaf area density was low near the ground, so the wind speed at 5 cm was frequently greater than or about the same as at 20 or 40 cm. In addition, a normalized wind speed profile was constructed for the fallow area using the logarithmic wind speed profile assuming a roughness length of 0.2 cm.

Fig. 5 illustrates the upward shift of air as it moves from fallow to 20 m inside the sorghum plot. This upward movement was computed using the continuity of mass principle of fluid dynamics. The assumption that the profiles can be normalized with respect to the wind speed at height of 410 cm is a reasonable approximation which can be deduced from the data of Kutzbach (1961) and Stearns and Lettau (1963). Actually the wind flow at 410 cm over the fallow should be slightly less than that over the leading edge of the sorghum.

Fig. 5 implies that the jump in temperature at a given height above ground (Fig. 2 and 3) can be explained by the upward movement of air to higher levels, as the boundary between a smooth and a rough surface is crossed. In some cases in the irrigated plot the averages of the 5-cm, 20-cm, and 40-cm temperature data did not show an increase, but showed a decrease upon crossing the plot boundary. This behavior is probably due to the greater rate of transpiration in the irrigated plot, which would result in the air being cooled faster than in the dryland plot. This explanation is substantiated by the bigger increases in vapor pressure in the irrigated plot than in the dryland plot as the air moved from fallow to 7 m inside.

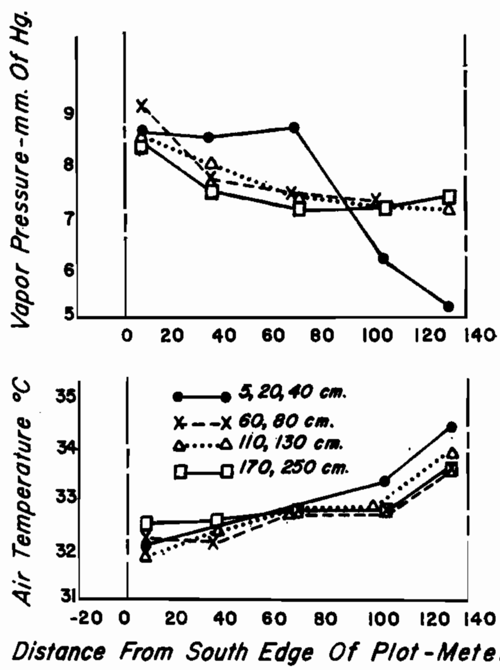


Fig. 4. Air temperature and vapor pressure as a function of height and distance from the south edge of the irrigated plot (downwind) on August 25, 1967 at 1515 MST.

Once inside the plot, the air temperature generally decreased on the irrigated plot on August 22 (Fig. 2). Most of this decrease occurred between 7 and 38 m from the south edge of the plot. This decrease was about 1 to 2 C. There was still a slight decrease at

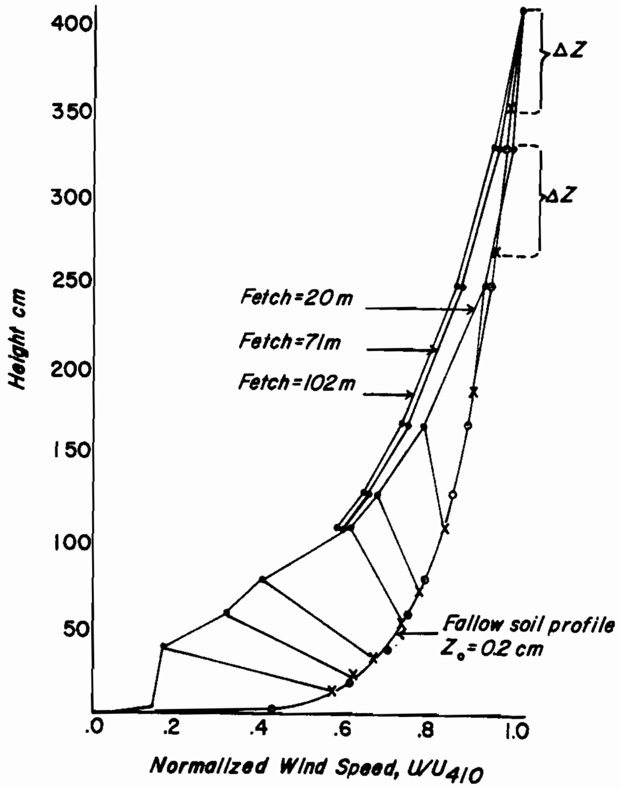


**Fig. 5. Normalized wind speed profiles on August 24, 1967 over the dryland plot with southerly winds. The profile over fallow was computed from the log wind speed profile law assuming $z_0 = 0.2$ and flow at the 410-cm level was the same as over the crop. The lines connecting the fallow profile to the 20-m fetch profile represent the equivalent upwind displacement of air on crossing from the fallow to the sorghum plot. Continuing changes at 71 m and 102 m show the approach to profile equilibrium downwind of the surface discontinuity. The 20-m fetch represents one profile, the 71-m fetch profile is an average of five runs, and the 102-m profile is an average of two runs. The stability ratio, $\Delta T/U^2$, for the 110- to 250-cm interval was 0.084 for the 20-m fetch profile and averaged 0.059 for the 71-m fetch profile and 0.053 for the 102-m fetch profile.**

all but the 170 to 250-cm measurement heights from 38 to 129 m, but it was less than 0.5 C. On August 25 (Fig. 4), when the wind was blowing from the north, no measurements were made in the fallow area. In general, temperatures also decreased from the upwind side into the plot. However, there was a temperature decrease of greater than 0.5 C from 38 to 129 m from the upwind (north) end.

The dryland plot (Fig. 3) showed about the same temperature trends as the irrigated plot, with an increase in temperature at most heights from the fallow to 7 m from the south (upwind) edge. From 7 to 38 m there was a temperature decrease, after which very little temperature change occurred. After the leading edge is crossed, many of the fluctuations in the temperature and vapor pressure data with distance downstream may be due to decelerations, accelerations, updrafts, and vorticity introduced in crossing over to a rough surface.

The vapor pressure data for August 22 (Fig. 2) shows a large vapor pressure increase from the fallow to the 7-m position, from the upwind edge position, especially within the canopy. Thereafter, there is very little vapor pressure change, with a trend for vapor pressure increase at the upper levels and a decrease at the lower levels. On August 24 (Fig. 3), the dryland plot shows a vapor pressure increase at the upwind edge from the fallow to the 7-m position. Thereafter, the general trend seems to be a slight vapor pressure decrease. On August 25 (Fig. 4) the irrigated plot data show a pronounced increase in vapor pressure from the upwind to the downwind edge of the plot. The August 22 and 24 data show a sharp increase in vapor pressure as the air flow crossed the plot boundary. These data, along with the wind speed profile of Fig. 5, show that the plants modify the local microclimate very rapidly over short distances downwind from the plot border. The potentially harsh advective environment of the plants *at* the plot border may be reduced somewhat by a larger lateral rooting zone with no competition for soil moisture.

The data show definite horizontal gradients of temperature, especially within about 40 m of the upwind edge. Since the wind direction changed considerably during the study period, it would appear that horizontal "edge effect" advection was one of the reasons the measured evapotranspiration was higher than predicted by the energy budget–Bowen ratio equation using the sweeping boom sampling apparatus. Thus, it would appear that this size of plot was too small to eliminate serious edge effects at any one position in the plot. This problem is probably much more serious with the wide row crop studies here than dense crops studies by most people earlier.

Within-canopy advection was important in the crop energy balance with this wide-row crop. A large amount of energy, originally used to heat up soil between rows, ended up supplying some of the energy used for transpiration. Near midday the soil surface temperature was nearly 20 C higher than the adjacent plot temperature (Fig. 6). There was less than 40% soil cover throughout the season as measured by photographs taken from about 8 m above the crop (data of J. T. Wooley, in Hanks et al.[3]). Consequently,

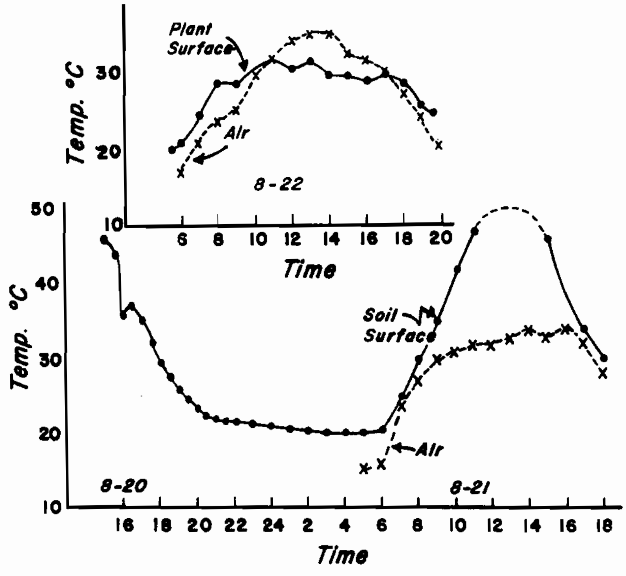


**Fig. 6. Plant and soil temperature measured with an infrared thermometer. Air temperature measured over irrigated plot with aspirated thermocouples.**

a large proportion of the incoming solar radiation was adsorbed by the soil surface.

Plant leaf temperature was monitored continuously on August 22 and 23 with a Barnes IT-3 infrared radiation thermometer, and soil temperature was monitored on August 20 and 21. Figure 6 shows the daily course of air, plant, and soil temperatures. The plant temperature at the top of the crop was higher than air temperature until afternoon, after which air temperature rose above leaf temperature. These data are in qualitative agreement with temperature lapse above the canopy in the afternoon.

Figure 7 shows water vapor concentration profiles, and Figure 8 shows air temperature profiles for the 10-level sampling system on August 22. Similar data for August 23, 24, 25, and 29 were used to calculate the heat and water vapor transfer characteristics above and below the plant canopy. The inverse slope of the lines in $\Delta T/\Delta\rho_v$ was used to calculate the Bowen ratio

$$\beta = A/lE = (\rho C\rho K_H \Delta T/\Delta Z)/(lK_v\Delta\rho_v/\Delta Z) \quad [1]$$

Where $\beta$ = the Bowen ratio, A = sensible heat flux density, lE = latent heat flux density, $C\rho$ = heat capacity of air at constant pressures, $\rho$ = density of air, $l$ =heat of vaporization of water, $K_H$ = transport coefficient for sensible heat, $K_v$ = transport coefficient for water vapor, $\Delta Z$ = height increment, $\Delta T$ = temperature difference over $\Delta Z$ and $\Delta\rho_v$ is water vapor concentration difference over $\Delta Z$. Under the assumption that $K_H = K_v$, this equation becomes

$$\beta = (\rho C\rho/l)\ (\Delta T/\Delta\rho_v) \quad [2]$$

where $\rho C\rho$ = .042 at Akron, Colorado.

There was a significant difference between the Bowen ratio above the crop from that below the canopy as shown in Table 4. Late in the afternoon, and/or under conditions of heavy cloud cover, the above-crop Bowen ratios became negative. The data on August 22 at 1455 and 1552 MST and on August 25 at 1500 and 1540 MST show this phenomenon in the irrigated plot. The 1755, 1825, and 1905 MST profiles on August 23 show this effect in the dryland plot. All of these "profiles" showed heat being transferred downward from above the canopy and upward from the soil surface.

Latent heat flux and sensible heat flux above and below the canopy were computed from

$$lE = (R_n - S)/(1 + B) \quad [3]$$

$$A = (R_n - S) - lE \quad [4]$$

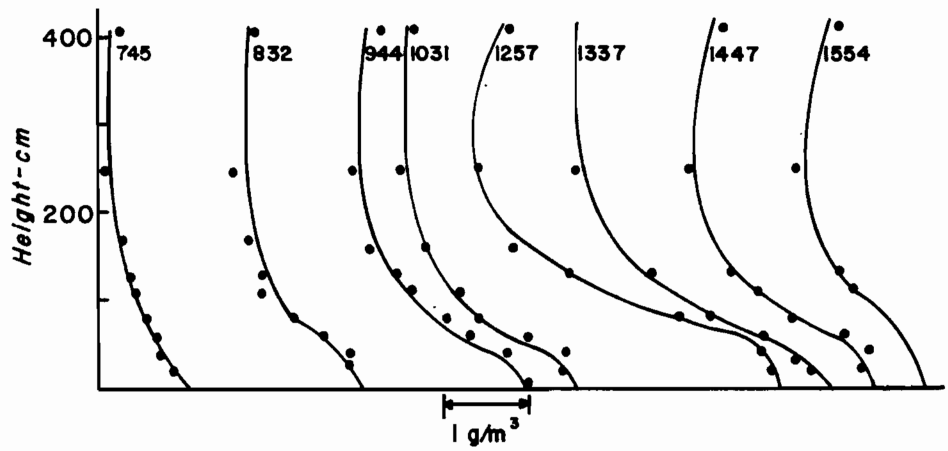


**Fig. 7. Water vapor content profiles on August 22, 1967 in the irrigated plot. The times given are the midpoints of 15-minute sampling periods and are in mountain standard time. Winds were southerly.**

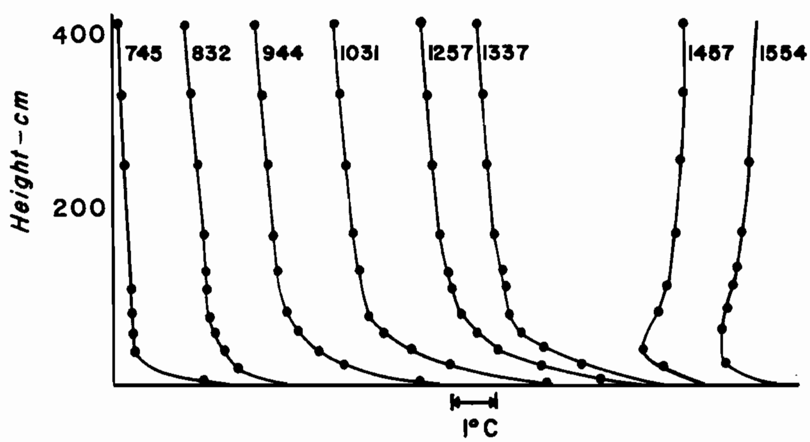


**Fig. 8. Temperature profiles for August 22, 1967 in the irrigated plot. The times given are the midpoints of 15-minute sampling periods and are in mountain standard times. Winds were southerly.**

where $R_n$ = net radiation above the canopy or computed net radiation at 20 cm and S = soil heat flux density.

The average penetration of net radiation at 20 cm in the irrigated plot was found to be 69% of that above the canopy, and the average penetration of net radiation at 20 cm in the dryland plot was 76% of that above (Hanks et al., 1970). These values of $R_n$ were used for that below-canopy calculations.

Table 4 summarizes the partitioning of sensible and latent heat above the canopy and below the canopy using graphical Bowen ratio determinations. The results for runs during high solar radiation periods are averaged for each day except August 25. This facilitates comparison, since $lE$ + A for the August 22, 23, and 24, averages were 0.418, 0.404, and .413 $cal/cm^2/min$, respectively. The later afternoon and early evening calculations give scattered results, probably because the soil heat flux measured at 5 cm depth lags the net radiation measurements.

The averages for the irrigated plot (August 23) and dryland plot (August 23) are contrasted in Table 4. Table 2 showed that these days had similar conditions of wind speed, temperature, relative humidity, and radiation.

$lE$ (above canopy) was greater for the irrigated plot than for the dryland plot 0.362 vs. 0.245 ly/min. $lE$ (below canopy) was low for both the irrigated plot and the dryland plot, 0.044 and 0.041 ly/min respectively. A (above canopy) was very low for the irrigated plot, 0.056 ly/min. A (below canopy) was greater for the dryland plot, 0.202 ly/min, than for the irrigated plot, 0.154 ly/min. About 64% of the A (below canopy) was used for transpiration in the irrigated grain sorghum, whereas only about 21% of the A (below canopy) was used for transpiration in the dryland grain sorghum. A (below canopy) used for transpiration was 0.098 ly/min in the irrigated plot and 0.043 ly/min in the dryland plot. The average $\beta$ (above canopy) was 0.158 for the irrigated plot and 0.654 for the dryland plot.

A dry front passed over the area on August 24 with the vapor density dropping from 9.8 to 6.1 $g/m^3$ from 900 to 1500 MST. Most of this drop (9.3 to 6.7 $g/m^3$ of water vapor) took place from 1100 to 1300 MST. Table 4 shows that the energy partition was changed upon passage of the dry front. Data were taken over the dryland grain sorghum plot that day. The $\beta$ above the canopy averaged 1.19 before the dry front and 0.372 after the dry front but did not change significantly below the canopy. $lE$ (above canopy) increased after passage of the dry front and A (above canopy) decreased after passage.

No net A (below canopy) was extracted by the plants before the passage of the dry front. However, after passage of the dry front about 42% of A (below canopy) was extracted by the plants.

These data show that external factors such as water vapor concentration can have a large influence on the partition of incoming radiant energy. We have evidence that on August 18 a combination of low temperature, high wind speed, and high water vapor concentration suppressed evapotranspiration (Hanks et al.[3]).

**Table 4. Partitioning of evapotranspiration ($lE$) and sensible heat (A) in wide-row grain sorghum at Akron, Colo., 1967. Subscripts b and a refer to below and above-canopy respectively.**

| Time | Bowen ratio | | Above | | Below | | | $\frac{A_b-A_a}{A_b}$ | $\frac{A_b}{R_n-S}$ |
|---|---|---|---|---|---|---|---|---|---|
| | Above | Below | $lE$ | A | $lE$ | A | $A_b-A_a$ | | |
| | | | ly/min | | | | | % | |
| | | | August 22, irrigated plot | | | | | | |
| 746 | .037 | 2.16 | .222 | .008 | .036 | .079 | .071 | 90 | 34 |
| 830 | .101 | 6.00 | .282 | .028 | .021 | .128 | .100 | 78 | 41 |
| 942 | .153 | 4.79 | .364 | .056 | .034 | .163 | .107 | 66 | 39 |
| 1029 | .262 | 6.89 | .301 | .079 | .017 | .118 | .039 | 33 | 31 |
| 1255 | .113 | 2.16 | .512 | .058 | .098 | .212 | .154 | 73 | 37 |
| 1335 | .161 | 2.99 | .353 | .057 | .049 | .147 | .090 | 61 | 36 |
| 1455 | .187 | 16.00 | .123 | -.023 | .002 | .024 | .047 | -- | 24 |
| 1552 | -.247 | 5.33 | .053 | -.013 | -.002 | -.008 | .005 | -- | -- |
| 830-1335 | .158 | 4.57 | .362 | .056 | .044 | .154 | .098 | (64%) | (37%) |
| | | | August 23, dryland plot | | | | | | |
| 850 | .756 | 6.89 | .216 | .164 | .031 | .211 | .047 | 22 | 56 |
| 950 | .672 | 2.99 | .245 | .165 | .063 | .189 | .024 | 13 | 46 |
| 1055 | .756 | 6.00 | .245 | .185 | .037 | .200 | .015 | 8 | 47 |
| 1245 | .790 | 4.37 | .251 | .199 | .050 | .218 | .019 | 9 | 48 |
| 1335 | .685 | 12.00 | .226 | .154 | .016 | .198 | .044 | 22 | 52 |
| 1425 | .517 | 3.42 | .310 | .160 | .069 | .238 | .078 | 33 | 51 |
| 1520 | .399 | 6.89 | .222 | .088 | .023 | .162 | .074 | 46 | 52 |
| 1755 | -.672 | -.790 | -.183 | .123 | -.252 | .199 | .076 | -- | -- |
| 1825 | -1.97 | -.406 | .093 | -.183 | -.131 | .065 | .248 | -- | -- |
| 1905 | -4.79 | -.201 | .011 | -.051 | .014 | .000 | .051 | -- | -- |
| 850-1520 | .654 | 6.08 | .245 | .159 | .041 | .202 | .043 | (21%) | (50%) |
| | | | August 24, dryland plot | | | | | | |
| 650 | .991 | 5.33 | .100 | .100 | .023 | .124 | .024 | 19 | 62 |
| 820 | 0.47 | 3.99 | .158 | .232 | .053 | .212 | -.020 | -9 | 54 |
| 940 | 1.10 | 2.65 | .214 | .236 | .080 | .212 | -.024 | -11 | 47 |
| 1045 | .991 | 5.33 | .246 | .244 | .049 | .263 | .019 | 7 | 54 |
| 1245 | .437 | 6.00 | .320 | .140 | .040 | .240 | .100 | 42 | 52 |
| 1345 | .352 | 3.99 | .274 | .096 | .043 | .171 | .075 | 44 | 46 |
| 1450 | .328 | 2.65 | .241 | .079 | .050 | .131 | .052 | 40 | 41 |
| 820-1450 | .780 | 4.10 | .242 | .171 | .052 | .205 | .034 | (16%) | (49%) |
| | | | August 25, irrigated plot | | | | | | |
| 830 | .044 | 8.02 | .297 | .013 | .019 | .151 | .138 | 91 | 49 |
| 1020 | .090 | 24.1 | .312 | .028 | .004 | .107 | .079 | 74 | 31 |
| 1500 | -.085 | 6.01 | .175 | -.015 | .003 | .021 | .036 | 171 | 13 |
| 1540 | -.090 | 3.99 | .220 | -.020 | .011 | .043 | .063 | 146 | 21 |
| | | | August 29, irrigated plot | | | | | | |
| 815 | .328 | 2.99 | .226 | .074 | .045 | .134 | .060 | 45 | 45 |
| 915 | .052 | 8.02 | .171 | .009 | .009 | .072 | .063 | 88 | 40 |
| 1030 | .157 | 3.69 | .242 | .038 | .028 | .103 | .065 | 63 | 37 |
| 1255 | .129 | 3.42 | .195 | .025 | .022 | .077 | .052 | 68 | 35 |
| 1350 | .059 | ∞ | .047 | .003 | -- | -- | -- | -- | -- |
| 815-1255 | .167 | .453 | .208 | .0365 | .026 | .0965 | .060 | (62%) | (39%) |
| | | | August 24, dryland, before dry front | | | | | | |
| 820-1045 | 1.19 | 3.99 | .206 | .237 | .061 | .229 | -.008 | (4%) | (52%) |
| | | | August 24, dryland, after dry front | | | | | | |
| 1245-1450 | .372 | 4.21 | .278 | .105 | .044 | .181 | .076 | (42%) | (46%) |

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# Nitrate-nitrogen Accumulation Under Bromegrass Sod Fertilized Annually at Six Levels of Nitrogen for Fifteen Years[1]

K. L. Larson, J. F. Carter, and E. H. Vasey[2]

**ABSTRACT**

**An old bromegrass sod established prior to 1929 and fertilized annually since 1954 with nitrogen at rates from 0 to 298 kg/ha responded with increased forage, protein, and seed yields. Nitrate-N content of the soil profile after 15 years of fertilization was analyzed using an Orion 401 specific ion meter with a $NO_3$-N electrode to determine the possible pollution of ground water with nitrates attributable to increased nitrogen fertilization. Nitrate-N content was similar below 106.7 cm to a selected depth of 137 cm during late April and of 152 cm during late June and August in 1969 under each of six fertility treatments. Highest concentration of $NO_3$-N was found in the soil profile from 15.2 to 61.0 cm in depth. Results suggest apparent lack of $NO_3$-N movement and accumulation in fine-textured soils under northern climatic conditions even under high rates of continuous nitrogen fertilization.**

***Additional index words:*** **$NO_3$-N, Nitrogen fertilization.**

NITROGEN usage on grasslands is expected to increase as nitrogen becomes more readily available at reduced prices and as farmers and ranchers recognize the economic and productive advantages of grassland fertilization. Possible pollution of ground water with nitrates attributable to increased nitrogen fertilization of grasslands has caused concern to many individuals. However, various investigators (3, 4, 5, 7) have shown $NO_3$-N does not move or accumulate appreciably to great depth in medium to fine-textured soil profiles.

Accumulation of $NO_3$-N below 180 cm in deep loess-derived profiles of silty clay loam and silt loams heavily fertilized in eastern Nebraska cropped to irrigated corn has been found to be very low and not appreciably in excess of amounts found in unfertilized soils (3). Species vary in ability to utilize $NO_3$-N from the soil profile (2, 4). Bromegrass roots in the 120- to 150-cm depths have been calculated to be 300 times more active in absorption of $NO_3$-N than roots in the surface soil in eastern Nebraska (5). Very little difference was found at the Grassland Research Institute at Hurley between orchardgrass and red fescue in relative ability to absorb nitrogen at various depths in the soil, although orchardgrass probably was more efficient (4). Orchardgrass recovered substantial amounts of nitrogen from 45 to 60 cm of the soil profile. Roots frequently penetrate soils to great depths but may vary greatly for a single species because of soil properties (6).

## MATERIALS AND METHODS

An old bromegrass sod established prior to 1929 at Fargo, N. D. was used as the experimental site. The soil type is Fargo clay. In 1954 and each succeeding fall, 0, 37, 74, 149, 224, and 298 kg of nitrogen/ha in the form of ammonium nitrate (33.5-0-0) were applied broadcast to the same 6.1 × 6.1-m plots replicated twice in a randomized complete block design. Forage and seed yields were obtained from 1955 and 1958 to 1969, respectively, by harvesting half of each plot for forage and the remaining half for seed. Two harvests annually were obtained for forage during 7 of the years the trial was conducted, and only one harvest in the remaining years due to seasonal summer drought. In all years except one, following seed harvest, the portion of plot harvested for seed was clipped to a 2.5-cm stubble. Recovery growth in the fall was left intact on the plots.

Soil samples to the depth of 137 cm were taken April 29, 1969 from each plot and partitioned into 15.2-cm segments for $NO_3$-N analyses. Additional samplings to 152 cm were taken June 27 and August 28, 1969. One boring per plot was taken, and duplicate plots were sampled. Soils samples were spread out for air drying within 3 hours after collection. The air-dry samples were stored until $NO_3$-N analyses were determined using an Orion 401 specific ion meter with a $NO_3$-N electrode in the Soil Testing Laboratory at North Dakota State University.

## RESULTS AND DISCUSSION

Forage and seed yields from 1955 and 1958 to 1969, respectively, are shown in Table 1. Increases of forage

**Table 1. Average forage and seed yields of bromegrass fertilized with six rates of nitrogen at Fargo.**

| Kg N/ha | Metric tons DM/ha 1955-69 | Kg clean seed/ha* 1958-69 |
|---|---|---|
| 0 | 2.38 | 36 |
| 37 | 3.50 | 64 |
| 74 | 5.04 | 81 |
| 149 | 5.94 | 92 |
| 224 | 6.66 | 119 |
| 298 | 7.08 | 160 |

* Seed harvesting initiated in 1958.

[1] Contribution from Departments of Agronomy and Soils. North Dakota Agr. Exp. Sta., Fargo, N. Dak. Published with approval of the Director of the North Dakota Agr. Exp. Sta. as Journal Article No. 260. Received for publication August 1, 1970.

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