Partitioning soil-water losses in different plant populations of dry-land corn

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Abstract

In situ volumetric soil-water contents were measured on 11 days at 0.20 m depth intervals to 1.0 m in a field experiment with four replicates of a dry-land corn hybrid (Pioneer 3140) at plant populations of 37, 49, and 62 thousand plants ha⁻¹. These measurements were used to estimate total soil-water losses in each of the 12 field plots for each of the 10 measurement intervals. The area of the largest leaf on 10 plants in each plot was measured at 86 days after planting, when all the leaves on the plants were fully developed. Daily green leaf area indexes (GLAI) were calculated from these measurements. Climatic data collected at the experimental site together with the results for GLAI were used to calculate water balances in order to partition the total soil moisture loss for each measurement interval into bare soil evaporation, crop transpiration, and drainage below the root zone. The observed total soil moisture losses between the days of measurement compared well with values from the water-balance calculations. As plant population increased, the time to full canopy cover increased. Therefore, higher fractions of the soil water were lost to bare soil evaporation and drainage over time as the plant population was lowered. At the same time, the fraction lost to crop transpiration decreased as the plant population was lowered. This compensatory effect under dry-land conditions resulted in almost identical total water losses by the three plant populations during the growing period. The calculated partitioning of the soil-water losses served to explain the experimental observations that, under dry-land conditions, it would be unlikely that total soil-water losses would be influenced by different plant populations of corn. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Leaf area index; Soil evaporation; Crop transpiration; Soil-water storage; Potential evapotranspiration; Penman equation

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1. Introduction

Maize (*Zea mays* L.) ranks third among the world cereal crops after wheat and rice. It is a major food and feed grain crop in the US (USDA, 1997). Maize is mostly grown under dry-land conditions meaning that its growth, development, and yield depends on limited seasonal rainfall. There has been a continuous effort to understand the inter-relationships between crop growth and development and soil-water availability in order to develop better dry-land soil and crop management practices (Butler and Prescott, 1955; Veihmeyer and Hendrickson, 1955; Denmead and Shaw, 1962; Shaw, 1963; Holmes and Robertson, 1963; Ritchie, 1973; Tanner and Jury, 1976; Waldren, 1983; Herbst et al., 1996). However, an issue that has not been adequately resolved in these studies has been the effect of plant populations on the partitioning of soil-water losses and on soil-water use efficiency. It is well known that crop grain yield increases as the total water transpired during the growing season (Veits, 1966; Monteith, 1979; Doorenbos and Kassam, 1979). A study by Khosla and Persaud (1997a, b) and Khosla and Persaud (1998) showed that increasing plant population increased yields of dry-land corn and sorghum hybrids but not the total crop water use. This would imply that increasing plant population can increase the amount of soil water transpired (Et) relative to the soil-water evaporated directly from the soil surface (Es) and to the total soil-water extracted (Es + Et). It is difficult to separate Es and Et in the field although it is relatively easy to measure the total soil-water loss from the root zone over a given time interval. On the other hand, it is relatively easy to calculate the daily potential atmospheric evaporative demand from daily climatic data taken over the same interval. The atmospheric demand depends on the energy from solar radiation and air circulation (turbulent mass transfer) available for evaporation at the soil and leaf surfaces. If the calculated values of the atmospheric evaporative demand can be appropriately reduced by taking into account dynamic soil and crop effects it is possible to partition the evaporative soil-water extraction (evapotranspiration) into its Es and Et components, and to partition the total soil-water losses into its evapotranspiration and drainage components.

There are three stages (Idso et al., 1974) in loss of water by evaporation from bare soil. Stage I losses depend only on the potential atmospheric evaporative demand implying that water is freely available at the soil surface. Under dry-land conditions, Stage I losses occurs at this potential rate for relatively short periods following rain events when the degree of saturation in the uppermost layer of the soil profile is between unity and some lower value which depends on the soil type (Ritchie et al., 1972; Ritchie, 1972, 1973). The evaporation loss rate decreases below this potential rate as the upper soil surface layer dries out. This ‘falling rate’ evaporation depends on the rate of upward movement of water from the lower layers of the soil profile to the upper layers close to the soil surface. This rate continually decreases and eventually reduces to some constant and negligible value. The falling rate losses are termed as Stage II soil evaporation and is driven primarily by the humidity difference between the atmosphere and the soil surface. Cumulative losses, after Stage II evaporation is initiated, are linearly related to the square root of time (Gardner and Gardner, 1969; Gardner, 1974). Evaporation losses at the negligible constant rate are termed as Stage III soil evaporation. Bare soil evaporation can...
be estimated with good accuracy if the atmospheric demand and soil effects on Stage II evaporation is characterized.

The processes and mechanisms controlling the plant transpiration (Et) rate are relatively more complicated than for bare soil evaporation. Transpiration rate depends on the water available at the leaf surfaces. As for bare soil, if water is freely available at the leaf surfaces transpiration rate would be controlled primarily by the atmospheric demand. However, the rate of movement of water from the soil to the leaf surfaces is a dynamic catenary process (Van den Honert, 1948) and is controlled by characteristics of the soil and crop (Chinchoy and Kanemasu, 1974; Brown and Simmons, 1979; Biran et al., 1981; Feldhake and Boyer, 1986; Monson et al., 1986). Of the water stored in the soil only the portion between field capacity (FC) and the permanent wilting point (PWP) is usually considered as transpirable. Soil-water stored in this range would be extracted at some potential rate (Et$_{pot}$) controlled primarily by the atmospheric evaporative demand. However, it is still debated whether the uptake of this transpirable portion by the plants depends on the fraction of this transpirable portion of the soil water that is actually present in the rooting zone (Butler and Prescott, 1955; Denmead and Shaw, 1962; Veits, 1966; Doorenbos and Kassam, 1979). Studies have suggested that the ratio (Et/Et$_{pot}$) of transpiration (Et) to potential transpiration (Et$_{pot}$) (a) is unity in entire range of available soil water (Veihmeyer and Hendrickson, 1955; Glover and Forsgate, 1964), (b) is unity in three-fourths of the transpirable soil-water range and then decreases sharply (Penman, 1949), (c) decreases linearly from the upper to the lower limits of the available soil-water range (Thornthwaite and Mather, 1955; Halstead, 1954; Wu, 1967), (d) is monotonically decreasing and curvilinear (West and Perkman, 1953; Butler and Prescott, 1955; Eagleman and Decker, 1956; Pierce, 1958; Knoerr, 1961).

In field crops the processes of soil-water extraction due to Es and Et at any given time are coupled. Thornthwaite (1948) defined the maximum possible sum of Es and Et in a growing crop as “the water loss which will occur if at no time there is a deficiency of water in the soil for use of vegetation.” In a dry-land crop, this maximum possible sum can be taken as equivalent to the atmospheric demand and is termed as the potential evapotranspiration (PET) as opposed to actual evapotranspiration (AET) due to specific soil and crop effects on Es and Et. Much thought has been put into quantifying the relationships between AET and PET. Maximum rates of evaporation and transpiration depend on several factors, such as temperature, humidity, wind velocity, vegetation characteristics (density, growth, leaf shape and orientation, species, rooting depth, etc.), nature of the evaporating surface, time of the day, season, geographic location. A variety of equations are used to calculate the potential atmospheric evaporative demand from climatic data. A rating of 20 popular equations for calculating the potential atmospheric evaporative demand (ASCE, 1990) showed that the most accurate estimates are obtained from various forms of the Penman equation (Penman, 1948, 1949).

A critical factor influencing Es and Et is the crop cover as measured by the green leaf area index (GLAI). As the GLAI increases the energy available for Es would decrease due to the increased shading of the soil surface. At the same time, the energy available for Et would increase due to the increased interception of solar radiation by the plant canopy. It has been shown that GLAI can be calculated with reasonable accuracy from simple plant measurements and accumulated thermal units during the growing period (Watson,
1947; Dwyer and Stewart, 1986; Muchow and Carberry, 1989). The effect of increasing GLAI on energy available for Es and Et can be estimated using a modified form of Beer’s law for light transmission through materials (Childs et al., 1977; Stapper and Arkin, 1980; Jones and Kiniry, 1986). As a result, it is relatively easy to estimate a dynamic balance of soil-water losses in field soils from rainfall inputs and estimates of Es and Et based on atmospheric evaporative demand calculated from climatic data. This dynamic balance would account for these effects of plant cover and transpirable soil water on Es and Et (Ritchie, 1972, 1973)

A question that needs to be resolved is how different plant populations of dry-land crops affect the partitioning of evaporative soil-water losses obtained from these calculated estimates of Es and Et. The objective of this study was to quantify the contribution of Es and Et to total soil-water losses as influenced by plant populations in dry-land corn. Specifically to:

1. Measure the total soil water losses in different plant populations of dry-land corn at intervals during the growing period.
2. Calculate the values of the stages I and II components of Es and also the Et during these intervals using Penman estimates of potential evaporative demand as modified by dynamic changes in soil and crop conditions.
3. Quantify the effect of the different plant populations on the Es and Et losses relative to the total soil-water losses.

2. Materials and methods

2.1. Field experiment

A field experiment was conducted during the summer of 1994 at Tidewater Agricultural Research and Extension Center (AREC), Suffolk, Virginia. The plots were laid out on a Uchee loamy sand (loamy, siliceous, thermic, Arenic Hapludult) in a field having a slope of <3%. Prior to planting, the experimental area was chisel-plowed to a depth of 0.3 m. Plots measuring 9.14 × 3.66 m² were arranged in a randomized complete block design with four plots per block. Blocks were laid out across the slope. Maize hybrid Pioneer 3124 was planted on April 19, 1994 on a 0.91 m row spacing. Plant densities after thinning were 37, 49, and 62, thousand plants ha⁻¹.

After thinning, 10 plants were tagged in each plot. Leaves on these plants were numbered as they appeared. At 86 days after planting, when all the leaves were fully expanded, the total number (N) of fully expanded leaves, together with the length (from junction of leaf blade and sheath to its tip) and maximum width of the largest leaf, and its leaf number (J) were measured on these tagged plants.

Recommended fertility management practices were used to ensure adequate nutrients for crop growth. Fertilizer applications were based on the results of soil chemical analyses for plant available nutrients on composite soil samples from 0 to 0.2 m depth. Based on the results of these analyses, 56 kg ha⁻¹ P₂O₅, 168 kg ha⁻¹ K₂O, and 140 kg ha⁻¹ N were applied. Small amounts of magnesium, manganese, and
boron were applied as a foliar spray 30 days after planting. The insecticide Orethene was applied at a rate of 2.3 kg ha\(^{-1}\) as needed to control sporadic infestation of thrips on the crop.

A soil pit was dug in the experimental field and three soil core samples were taken from each horizon in the soil profile. Particle size distribution, particle density, bulk density, and water retention at a pressure \(-1.5\) MPa were determined on these samples using standard methods. Soil volumetric water content measurements were taken in all plots at \(\approx 10\)-day intervals after crop emergence throughout the growing season. Measurements were made at 11, 25, 35, 45, 50, 57, 65, 74, 86, 100, and 115 days after planting. A resonant frequency capacitance probe, model Sentry 200-AP, manufactured by Troxler Electronic Laboratories, was used to measure soil volumetric water content in situ at five equal depth intervals from 0 to 1 m in the soil profile. The instrument was calibrated (Khosla and Persaud, 1997a) for the soil profile at the experimental site. To lower the probe into the soil profile, Schedule 40 PVC access tubes, having 0.052 and 0.061 m inner and outer diameter, respectively, were installed in the center of each experimental plot. Holes for installation of these access tubes in the experimental plots were made using a special hand auger supplied by Troxler. Soil-water extraction for an interval between measurements was calculated as the algebraic sum of the cumulative precipitation for the interval and the measured change in the soil-water storage during that interval.

As grain filling progressed, cobs were periodically examined to see if the grains had developed a black abscission layer, an indication that grain filling was complete. Grain filling was complete between 120 and 125 days after planting. Data on grain yields were obtained on the cobs that were hand harvested from the two middle rows of each plot at the time of harvesting. Grain yield was adjusted to 0% moisture content. Prior to harvesting the plots, an area measuring 1.82 \(\times\) 1 m\(^2\) in size was demarcated around each of the PVC access tubes used for moisture measurement. The number of plants and the number of cobs were recorded for each of these micro-plots. The plants were then cut from the ground level, the cobs were harvested, and the grains were separated by hand. All the stover was then collected and dried at 70°C to a constant weight. The grain yield from the micro-plot was combined with the yield from the remainder of the plot to obtain the whole plot yield. The total above ground dry matter yield ha\(^{-1}\) was estimated by adding the grain yield adjusted to 0% moisture content, to the dry stover yield ha\(^{-1}\) estimated from the stover yield for each micro-plot.

Meteorological data consisting of daily maximum and minimum temperatures, precipitation, solar radiation, relative humidity, and wind run were obtained using an automated weather station. Measurements were recorded at 10 min intervals. Daily averages were computed for the maximum and minimum temperature and relative humidity. The data on the other climatic elements were accumulated to obtain a daily total.

2.2. Calculation of GLAI

The accumulated thermal units \((C)\) on any day after planting were calculated as the sum of the daily values of the average of the daily maximum and minimum temperature
minus the base temperature of 8°C. During the grain filling period beginning two days after anthesis until maturity, a base temperature of 0°C was used (Muchow et al., 1990; Muchow and Sinclair, 1991). The area (AMAX) of the largest leaf (with leaf number ‘J’) on each tagged plant at 86 days after planting was determined as the product of 0.75 and its measured length and its maximum width (McKee, 1964). These values were then used to estimate GLAI for any growth stage with \( N_t \) fully expanded leaves as proposed by Muchow and Carberry (1989):

\[
\text{GLAI} = \frac{P}{10000} \sum_{i=1}^{M} \text{AMAXe}^{[-0.0344(i-J)^2 + 0.000731(i-J)^3]} \\
M = \text{INT}(2.5e^{0.00225C}) + 2 \quad \text{for } N_t < N
\]

In the first equation, \( P \) represents the plant population (plants \( m^{-2} \)) and AMAX is in \( cm^2 \) (the divisor 10000 represents the conversion from \( cm^2 \) to \( m^2 \)). The first term \( (1 - \alpha e^\beta C) \) represents the fraction of non-senesced leaves as a function of the accumulated thermal units, \( C \), using a base temperature of 8°C prior to anthesis and 0°C during grain filling (Muchow and Sinclair, 1991). In this term, the value of \( \alpha = 0.00161 \) and \( \beta = 0.00328 \) (Dwyer and Stewart, 1986; Muchow and Carberry, 1989). The first term of the second equation estimates the whole number \( (N_t) \) of fully expanded leaves at any given time as a function of the phenological time scale \( C \). Two is added to the value of \( N_t \) to calculate ‘\( M \)’ in order to account for expanding leaves as proposed by Muchow and Carberry (1989). The total numbers of leaves at maturity is represented as \( N \). They observed that the combined area of all the leaves that are not fully expanded on a plant at a given time was equal to the fully expanded area of the two leaves immediately above the last fully expanded leaf. The measured mean value of AMAX was used to calculate the GLAI for each experimental plot.

### 2.3. Calculation of the atmospheric evaporative demand

The original version of Penman’s equation (Penman, 1948) was used to calculate the atmospheric demand (PET) as

\[
\text{PET} = \frac{239\Delta R_n}{L(\Delta + \gamma)} + \frac{\gamma E_a}{\Delta + \gamma}
\]

where PET is given in mm day$^{-1}$, \( \Delta = de_s/dT \) in mb°C$^{-1}$ is the slope of the saturation vapor pressure (\( e_s \)) curve as a function of temperature, \( R_n \) in MJ m$^{-2}$ day$^{-1}$ is the net solar radiation available for evaporation at the evaporating surface, \( L \) in cal g$^{-1}$ is the latent of vaporization of water at a given surface temperature, \( \gamma \) in mb°C$^{-1} = 0.67 \) is the psychrometric constant, and \( E_a \) in mm day$^{-1}$ is a turbulent mass transfer function due to air circulation over the evaporating surface, the factor 239 is a conversion factor to homogenize the units.

The function \( E_a \) was calculated as \( E_a = 0.26 \times (1 + 0.0061U) \times (e_s - e_a) \) where \( U \) is the windrun in km day$^{-1}$, \( e_s \) in mb is the saturation vapor pressure at a given temperature, and \( e_a \) in mb is the actual vapor pressure at the given temperature.
The value of \( e_s \) at a given mean daily temperature (\( T_m = \) one half observed daily maximum + minimum temperature in °C) was calculated (Richards, 1971) as:

\[
e_s = ae^{b_1 T - b_2 T^2 - b_3 T^3 - b_4 T^4}
\]

where \( T = 1 - 373/(T_m + 273) \) and \( a = 1013.25, b_1 = 13.3185, b_2 = 3.952, b_3 = 1.9335, b_4 = 0.5916 \).

The value of \( \Delta \) was calculated as

\[
\Delta = e_s \left( \frac{373}{(T_m + 273)^2} \right) (b_1 T - 2b_2 T - 3b_3 T^2 - 4b_4 T^3)
\]

2.4. Calculation of bare soil evaporation and transpiration

Estimates of \( E_s \) and \( E_t \) were made by keeping a running daily account of the rainfall inputs and soil-water extraction in the maximum rooting depth which was taken as 1.0 m. The experimental field was in clean fallow prior to planting on April 19, 1994. Between March 1, 1994 and planting, a period of 50 days, 269 mm of rain fell at the site an average of 5.4 mm day\(^{-1}\). No rain fell during the week prior to the first moisture sampling on April 29, 1994. On this date, the soil profile to 1.0 m depth was assumed to be as close to field capacity as could be estimated in the field. The volumetric water contents on the first measurement date and the measured values of the volumetric water content at \(-1.5 \) MPa were used to estimate the maximum available water stored in the 1.0 m depth of the soil profile on that date for each of the 12 plots. These values were used as the starting values for the water-balance calculations for each plot. The mean and standard deviation of these estimated water storage in the 12 plots on the first measurement date was 88 ± 19 mm.

Stage I evaporation was restricted to the uppermost 0.05 m of the rooting depth. This depth was based on visual field observations of soil surface wetness on several days after rainfall. Available water stored in this layer between field capacity (FC) and the permanent wilting point (PWP) was 4 mm and was subject to Stage 1 evaporation as long as the atmospheric evaporative demand at the soil surface did not exceed the water stored in this 0.05 m layer. The atmospheric demand for Stage 1 evaporation at the soil surface was calculated using the first term of Penman’s equation. This assumes that turbulent mass transfer does not contribute significantly to Stage 1 evaporation (Ritchie, 1972). The net solar radiation \( R_n \) (MJ m\(^{-2}\) day\(^{-1}\)) available for evaporation at the soil surface was calculated as \( R_n = \alpha R_s \text{e}^{(-0.4GLAI)} \) where \( \alpha \) is the albedo of the surface which increases from 0.1 for bare soil to 0.23 for full canopy cover as \( \alpha = 0.1 + 0.25 \times (0.23 - 0.1) \text{GLAI} \) (Ritchie, 1972), \( R_s \) is the observed solar radiation (MJ m\(^{-2}\) day\(^{-1}\)). Use of this procedure assumes negligible losses in \( R_n \) due to soil heating and outgoing long-wave radiation. It also assumes that sunlight transmission by the crop canopy follows Beer’s law with an extinction coefficient of 0.4 (Kiniry et al., 1989; Stapper and Arkin, 1980). Stage 1 evaporation, \( E_{s1} \) (mm day\(^{-1}\)), was calculated as \( 239R_n/L \) where \( L \) at a given daily mean temperature \( T_m \) (°C) was calculated as \( L = 595 - 0.51 \times T_m \). This assumes a negligible contribution of turbulent mass transfer (second term of Penman’s equation) to \( E_{s1} \)
Stage 2 evaporation, $E_{s2}$ (mm day$^{-1}$), commenced when the atmospheric evaporative demand at the soil surface exceeded the water stored in the uppermost 0.05 m layer. Stage II evaporation losses were extracted from the entire profile as a decreasing function of time. It was calculated (Ritchie, 1972, 1973) as:

$$E_{s2} = \lambda \left( \sqrt{t_i} - \sqrt{t_{i-1}} \right)$$

where $\lambda = 3.3$ and $t_i$ is the $i$th day since the onset of Stage II evaporation. The total bare soil evaporation was then calculated as $E_s = E_{s1} + E_{s2}$.

The net solar radiation $R_n$ (MJ m$^{-2}$ day$^{-1}$) available for transpiration at the leaf surface was calculated as $R_n = \alpha R_s [1 - e^{(-0.4GLAI)}]$ which is equivalent to the radiation intercepted by the plant canopy for a given value of GLAI. This was used as input into Penman’s equation for calculating transpiration losses. When the total available water stored in the soil profile between field capacity (FC) and the permanent wilting point (PWP) decreased below 0.25 of its value the transpiration losses was reduced linearly by a factor $[(S - S_w)/0.25(S_f - S_w)]$ where $S$ [$S < 0.25(S_f - S_w)$] is the profile storage at a given time, $S_w$ is the storage at PWP and $S_f$ is the storage at field capacity. In addition, the turbulent mass transfer term in Penman’s equation was made dependent on GLAI by multiplying by the factor $(1 - 1.5 e^{-1.5GLAI})$. For GLAI > 2.7 this factor was ≈1 as suggested by Ritchie (1972). Any water in the soil above the transpirable capacity was considered to be drainable below the 1.0 m rooting depth. The amount drained on any day was increased exponentially as the ratio of the amount of water stored above field capacity on that day to the water stored between field capacity and saturation increased.

### 3. Results and discussion

Crop emergence was complete by the first soil-water measurement date at 11 days after planting with an accumulated thermal units (base temperature 8°C) of 117°C. Fully expanded leaves appeared at a rate of about one leaf for every 50 thermal units accumulated for a total of 19 leaves. On most plants the largest leaf area occurred on the 12th leaf. This value corresponds exactly to a calculated value of INT (12.3) = 12 for the largest leaf number ($J$) on corn plants as $J = 0.46N + 3.53$ where $N = 19$ is the total number of leaves (Muchow and Sinclair, 1991). Anthesis occurred when the accumulated thermal units was 959°C at 79–80 days after planting (69–70 days after emergence). The crop was fully matured at 120–123 days after planting corresponding to accumulated thermal units of 2052°C and 2127°C, respectively.

The measured areas of the largest leaf at 86 days after planting showed a marked reduction as plant population increased from 49 000 to 62 000 plants ha$^{-1}$. Treatment means and standard deviations were 0.0846 ± 0.0014, 0.0834 ± 0.0019, and 0.0756 ± 0.0026 m$^2$ for the plant population of 37 000, 49 000 and 62 000 plants ha$^{-1}$ respectively. Table 1 shows the soil physical properties measured prior to tillage operations for the Uchee loamy sand that was used for the field experiment. The clay content increased with depth. The dry bulk density values were high but were not atypical for the soils at the Tidewater station. Root observations in the soil pit indicated that plant roots were able to penetrate these layers. Soil pH decreased steadily with depth. Values
Table 1
Selected soil chemical and physical properties in the 0–1.0 m depth of the Uchee loamy sand

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Depth (m)</th>
<th>pH</th>
<th>Sand (g kg(^{-1}))</th>
<th>Silt (g kg(^{-1}))</th>
<th>Clay (g kg(^{-1}))</th>
<th>Texture</th>
<th>Bulk density (mg m(^{-3}))</th>
<th>Particle density (mg m(^{-3}))</th>
<th>Porosity (mg m(^{-3}))</th>
<th>Volumetric water content at 0.03 MPa</th>
<th>Volumetric water content at 1.5 MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap</td>
<td>0–0.33</td>
<td>6.1</td>
<td>800</td>
<td>183</td>
<td>17</td>
<td>Loamy fine sand</td>
<td>1.62</td>
<td>2.69</td>
<td>0.40</td>
<td>0.139</td>
<td>0.057</td>
</tr>
<tr>
<td>E</td>
<td>0.33–0.58</td>
<td>5.9</td>
<td>693</td>
<td>262</td>
<td>45</td>
<td>Loamy fine sand</td>
<td>1.83</td>
<td>2.67</td>
<td>0.32</td>
<td>0.208</td>
<td>0.086</td>
</tr>
<tr>
<td>BE</td>
<td>0.58–0.69</td>
<td>5.2</td>
<td>663</td>
<td>247</td>
<td>90</td>
<td>Loamy sand</td>
<td>1.85</td>
<td>2.69</td>
<td>0.32</td>
<td>0.250</td>
<td>0.109</td>
</tr>
<tr>
<td>Bt1</td>
<td>0.69–1.0</td>
<td>4.8</td>
<td>565</td>
<td>165</td>
<td>270</td>
<td>Sandy clay loam</td>
<td>1.71</td>
<td>2.76</td>
<td>0.39</td>
<td>0.287</td>
<td>0.238</td>
</tr>
</tbody>
</table>
were 6.1, 5.9, 5.2, and 4.8 for the Ap, E, BE, and Bt horizons, respectively. The maximum rooting depth for corn in this soil was therefore taken as 1.0 m. The particle size analysis data in Table 1 were used to estimate the soil texture using the USDA textural triangle. Porosity (calculated as 1 minus the ratio of the bulk density and the particle density) are reported along with the measured values of the volumetric water content at \(-0.033\) and \(-1.5\) MPa.

Calculated values of the GLAI on the dates of sampling are shown in Fig. 1 for the three plant populations. The general form of these curves were as expected. The GLAI reached a maximum at the same time 75 days after planting for all three plant populations. However, full canopy cover corresponding to \(\text{GLAI} = 2.7\) (Ritchie, 1972) was achieved earlier with increasing plant population. The time lag was greater between 37 000 and 49 000 plants ha\(^{-1}\) than between 49 000 and 62 000 plants ha\(^{-1}\). As would be expected, reduction in GLAI was almost the same due to senescence for all three plant populations.

Fig. 2 shows the comparison between the measured and calculated cumulative total water extraction for the three plant populations at the 11 dates of measurement. There was little difference between the cumulative totals between the three plant populations of 37, 49, and 62, thousand plants ha\(^{-1}\). The total water losses from the 1.0 m of the profile were ca. 400 mm for the three plant populations. This result was expected, since as plant population increases the transpiration increases but the greater shading tends to reduce bare soil evaporation. The calculated partitioning of the cumulative water extraction totals for the three plant populations into stages I and II evaporation, drainage below the 1.0 m root zone, and crop transpiration is presented in Table 2. Stages I and II evaporation were practically the same for the three populations. Drainage below the 1.0 m root zone decreased as the plant population increased but the variation was high due primarily to the high variation in the evaporable soil-water storage (88 \(\pm\) 19 mm) in the plots. Transpiration increased with increasing plant population. The increase was greater between 37 and 49 thousand plants ha\(^{-1}\) than between 49 and 62 thousand plants ha\(^{-1}\).
As shown in Fig. 3 (which shows a graph of the cumulative rainfall recorded at the site) during the period between crop emergence at 11 and 115 DAP a total of 379.4 mm of rainfall were recorded. Of this total 132.1 mm fell between 86 and 100 DAP (75–89 days).

Table 2
Calculated cumulative values (mean ± SE) for stages 1 and 2 evaporation, drainage below the root zone, and crop transpiration between 11 and 115 days after planting for three populations of dryland corn

<table>
<thead>
<tr>
<th>Population (Plants ha⁻¹)</th>
<th>Stage 1 evaporation (mm)</th>
<th>Stage 2 evaporation (mm)</th>
<th>Drainage below root zone (mm)</th>
<th>Transpiration (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>37 000</td>
<td>12.2 ± 0.6</td>
<td>102.6 ± 1.9</td>
<td>53.6 ± 10.4</td>
<td>227.3 ± 10.9</td>
</tr>
<tr>
<td>49 000</td>
<td>9.5 ± 2.2</td>
<td>101.3 ± 2.2</td>
<td>47.3 ± 22.2</td>
<td>244.4 ± 21.0</td>
</tr>
<tr>
<td>62 000</td>
<td>11.9 ± 1.0</td>
<td>100.9 ± 2.3</td>
<td>41.8 ± 11.5</td>
<td>250.5 ± 15.6</td>
</tr>
</tbody>
</table>
after emergence) and 78.5 between 100 and 115 DAP (89–104 days after emergence). Thus, 55.5% of the rain fell during the period after anthesis. The total water available for crop growth was the 379.4 mm rainfall and the initial water stored in the 1.0 m of the soil profile for each plot. The calculated mean and standard deviation values for the fraction of evaporable water present in the profile at 115 DAP (the last date of soil-water measurement) were, respectively, $0.84 \pm 0.01$, $0.76 \pm 0.05$, and $0.75 \pm 0.02$ for plant populations of 37, 49, and 62 thousand plants ha$^{-1}$. The mass balance for the calculated total soil-water losses during the period of measurement was therefore consistent and indicated no serious computational errors in the water-balance algorithms.

In general, the patterns of the calculated and measured values were similar (Fig. 2). The calculated values tended to be higher than the observed values. The discrepancies were generally small but increased with increasing plant population and during periods with little rain. The largest discrepancies occurred for all three plant populations during the period 64–68 days after emergence (74–78 DAP) which was a markedly dry period as illustrated in Fig. 3. During the period from 54 to 75 days after emergence (65–86 DAP) a total of 15.6 mm rain fell in six rain showers. A relatively large fraction of such small rain showers can be lost to interception, which was not accounted for in the calculation of the soil-water balances. As a result, the tendency would be for the calculated values to exceed the observed values during this period. Also, the calculation of the water balances assume that the transpiration decreased linearly as the fraction of the transpirable soil water decreased below 25%. If the transpiration did not decrease as assumed, the tendency would be again for the calculated values to exceed the observed values during this period. Nevertheless, the generally good agreement between the observed and measured total soil-water losses provided further validation of the procedures used for calculation of the soil-water balances. Another validation of the procedures was the constancy of the observed ratio of above ground dry matter yield to the amount of water transpired. The mean and standard deviation of these ratios for the plant populations of 37, 49, and 62, thousand plants ha$^{-1}$ were $50.5 \pm 15.0$, $52.5 \pm 9.9$, and $51.1 \pm 4.5$ kg mm$^{-1}$, respect-
It is generally accepted that above ground dry matter yield is linearly related to the amount of water transpired.

Fig. 4(a and b), respectively, show the contribution of the calculated bare soil evaporation (Es) and transpiration (Et) for the 10 intervals between the dates of measurement expressed as a percent of the calculated total soil-water losses from evaporation, transpiration, and drainage below the root zone during the specified interval. As expected, Fig. 4(a and b) show that the percentage of bare soil evaporation to total water loss in any interval was inversely related to plant population. The decrease was greater between 37,000 and 49,000 plants ha\(^{-1}\) than between 49,000 and 62,000 plants ha\(^{-1}\) mirroring the population effect on GLAI. Fig. 4(a) shows that in the 14-day period after emergence (11–25 DAP), the percentage was almost similar (34–35%) for all three plant populations but increased sharply during the next 10-day period (25–35 DAP). During the 14-day period after emergence a total of 58.9 mm of rainfall was received. The fraction of evaporable water in the profile for each plot was assumed to be unity at the beginning of water-balance calculations, and therefore, the calculated drainage during
the initial 14-day period was high. The calculated drainage during this initial period accounted for over 60% of the total drainage accumulated over the entire period between emergence and 115 DAP. As a result, the percentage of bare soil evaporation to the total losses during this initial 14-day period after emergence was lower than the percentage during the succeeding 10-day period (25–35 DAP). Thereafter, the percentages tended to decrease monotonically over time for all three plant populations. For all three plant populations, the percentage of the total water lost as crop transpiration for each measurement interval increased monotonically with time up to the period after anthesis; thereafter it tended to level off.

In their entirety, the calculated partitioning of the soil-water losses serve to explain the observations that these losses were not influenced by the different plant populations of corn under dry-land conditions. It seems clear that as the population increases the time to full canopy cover increases. Higher fractions of the soil water are lost to bare soil evaporation and drainage over time as the plant population is lowered. At the same time, the fraction lost to crop transpiration decreases as the plant population is lowered. This compensatory effect under dry-land condition resulted in almost identical total water losses by the three plant populations during the growing period.

References


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